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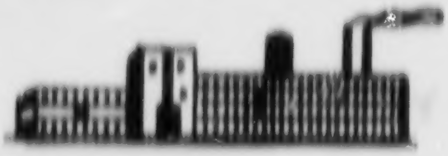

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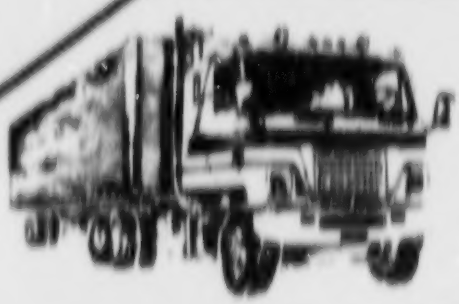
SECOND EDITION

(Third Printing with Supplements 1–5)



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16. ABSTRACT

Emission data obtained from source tests, material balance studies, engineering estimates, etc., have been compiled for use by individuals and groups responsible for conducting air pollution emission inventories. Emission factors given in this document, the result of the expansion and continuation of earlier work, cover most of the common emission categories: fuel combustion by stationary and mobile sources; combustion of solid wastes; evaporation of fuels, solvents, and other volatile substances; various industrial processes; and miscellaneous sources. When no specific source-test data are available, these factors can be used to estimate the quantities of primary pollutants (particulates, CO, SO_2, NO_x, and hydrocarbons) being released from a source or source group.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Fuel combustion Emissions Emission factors Mobile sources Stationary sources		

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Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina
February 1976

This report is published by the Environmental Protection Agency to report information of general interest in the field of air pollution. Copies are available free of charge to Federal employees, current contractors and grantees, and nonprofit organizations - as supplies permit - from the Air Pollution Technical Information Center, Environmental Protection Agency, Research Triangle Park, North Carolina 27711. This document is also available to the public for sale through the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

Publication No. AP-42

PREFACE

This document reports data available on those atmospheric emissions for which sufficient information exists to establish realistic emission factors. The information contained herein is based on Public Health Service Publication 999-AP-42, *Compilation of Air Pollutant Emission Factors*, by R.L. Duprey, and on two revised and expanded editions of *Compilation of Air Pollutant Emission Factors* that were published by the Environmental Protection Agency in February 1972 and April 1973, respectively. This document is a reprint of the second edition and includes the supplements issued in July 1973, September 1973, July 1974, January 1975, and December 1975 (See page iv). It contains no new information not already presented in the previous issuances.

Chapters and sections of this document have been arranged in a format that permits easy and convenient replacement of material as information reflecting more accurate and refined emission factors is published and distributed. To speed dissemination of emission information, chapters or sections that contain new data will be issued—separate from the parent report—whenever they are revised.

To facilitate the addition of future materials, the punched, loose-leaf format was selected. This approach permits the document to be placed in a three-ring binder or to be secured by rings, rivets, or other fasteners; future supplements or revisions can then be easily inserted. The lower left- or right-hand corner of each page of the document bears a notation that indicates the date the information was issued.

The availability of future supplements to *Compilation of Air Pollutant Emission Factors* will be announced in the publication *Air Pollution Technical Publications of the Environmental Protection Agency*, which is available from the Air Pollution Technical Information Center, Research Triangle Park, N.C. 27711 (Telephone: 919—549-8411 ext. 2753). This listing of publications, normally issued in January and July, contains instructions for obtaining the desired supplements.

Comments and suggestions regarding this document should be directed to the attention of Director, Monitoring and Data Analysis Division, Office of Air Quality Planning and Standards, Environmental Protection Agency, Research Triangle Park, N.C. 27711.

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Because this document is a product of the efforts of many individuals, it is impossible to acknowledge each person who has contributed. Special recognition is given to Environmental Protection Agency employees in the Technical Development Section, National Air Data Branch, Monitoring and Data Analysis Division, for their efforts in the production of this work. Bylines identify the contributions of individual authors who revised specific sections and chapters.

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Section 4.4 Marketing and Transportation of Petroleum Products	
Supplement No. 2	9/73
Introduction	
Section 3.1.1 Average Emission Factors for Highway Vehicles	
Section 3.1.2 Light-Duty, Gasoline-Powered Vehicles	
Supplement No. 3	7/74
Introduction	
Section 1.4 Natural Gas Combustion	
Section 1.5 Liquified Petroleum Gas Consumption	
Section 1.6 Wood/Bark Waste Combustion in Boilers	
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ABSTRACT

Emission data obtained from source tests, material balance studies, engineering estimates, etc., have been compiled for use by individuals and groups responsible for conducting air pollution emission inventories. Emission factors given in this document, the result of the expansion and continuation of earlier work, cover most of the common emission categories: fuel combustion by stationary and mobile sources; combustion of solid wastes; evaporation of fuels, solvents, and other volatile substances; various industrial processes; and miscellaneous sources. When no source-test data are available, these factors can be used to estimate the quantities of primary pollutants (particulates, CO, SO_2, NO_x, and hydrocarbons) being released from a source or source group.

Key words: fuel combustion, stationary sources, mobile sources, industrial processes, evaporative losses, emissions, emission data, emission inventories, primary pollutants, emission factors.

COMPILATION
OF
AIR POLLUTANT EMISSION FACTORS

INTRODUCTION

In the assessment of community air pollution, there is a critical need for accurate data on the quantity and characteristics of emissions from the numerous sources that contribute to the problem. The large number of individual sources and the diversity of source types make conducting field measurements of emissions on a source-by-source basis at the point of release impractical. The only feasible method of determining pollutant emissions for a given community is to make generalized estimates of typical emissions from each of the source types.

One of the most useful (and logical) tools for estimating typical emissions is the "emission factor," which is an estimate of the rate at which a pollutant is released to the atmosphere as a result of some activity, such as combustion or industrial production, *divided by* the level of that activity (also expressed in terms of a temporal rate). In other words, the emission factor relates the quantity of pollutants emitted to some indicator (activity level) such as production capacity, quantity of fuel burned, or vehicle miles traveled. In most cases, these factors are simply given as statistical or estimated averages; that is, no empirical information on the various process parameters (temperature, reactant concentrations, etc.) is considered in their calculation. However, for a few cases, such as in the estimation of hydrocarbon emissions from petroleum storage tanks, precise empirical formulas relating emissions to such variables as tank diameter, liquid storage temperature, and wind velocity have been developed. Because of their superior precision, emission factors based on empirical formulas are more desirable to obtain and can usually be given the highest accuracy rating. Factors derived from statistical averages, however, if based on an adequate number of field measurements ("source tests"), can also be both precise and accurate within practical and useful limits.

An example should illustrate how the factors are to be used:

Suppose a sulfuric acid plant, with a production rate of 200 tons/day of 100 percent acid, operates at an overall SO_2 to SO_3 conversion efficiency of 97 percent. Using the formula given as a footnote to Table 5.17-1 on page 5.17-5 of this publication, the *uncontrolled* sulfur dioxide emissions can be calculated :

$$\begin{aligned} SO_2 \text{ emissions } &= [-13.65\ (\%\text{ conversion efficiency}) + 1365] \times \text{production rate} \\ &= [-13.65\ (97\%) + 1365]\ \text{lb/ton acid} \times 200\ \text{tons acid/day} \\ &= 40\ \text{lb/ton acid} \times 200\ \text{tons acid/day} \\ &= 8000\ \text{lb/day}\ (3632\ \text{kg/day}) \end{aligned}$$

The emission factors presented in this report have been estimated using a wide spectrum of techniques available for their determination. The preparation/revision of each factor section involves, first of all, the search for and obtainment of all the known written information on that source category from such sources as the Air Pollution Technical Information Center literature, Environmental Protection Agency technical reports (including emission test reports), and the National Emissions Data System point source file. After these data are reviewed, organized, and analyzed, the process descriptions, process flowsheets, and other background portions of the section are prepared. Then, using the compiled information, representative emission factors are developed for each pollutant emitted by each point source of the process category. As stated above, these factors are usually obtained by simply averaging the respective numerical data obtained. When feasible, the ranges in the factors are presented for further clarity. Occasionally, enough data exist to permit the development of either empirical or theoretical formulas (or graphs) relating emissions factors to various process parameters such as stream temperature, sulfur content, or catalyst. In these cases, *representative* values of these process parameters are selected and substituted into the formulas or graphs that, in turn, yield representative emission factors which are then tabulated within. The pertinent formulas and graphical data are also included in the section to allow the estimation of emission factors when the process conditions differ from those selected by the author(s).

After the draft of a section is completed, it is circulated for technical review to various personnel routinely familiar with the emission aspects of the particular activity. After these review comments are obtained and evaluated, the final draft is written and submitted for editing and publication.

The limitations and applicability of emission factors must be understood. To give some notion of the accuracy of the factors for a specific process, each set of factors has been ranked according to the available data upon which it was based. Each rank was based on the weighting of the various information categories used to obtain the factor(s). These categories and associated numerical values were:

Measured emission data: 20 points, maximum
Process data: 10 points, maximum
Engineering analysis: 10 points, maximum

The emission data category rated the amount of measured (source test) data available for the development of the factor. The process data category involved such considerations as the variability of the process and its resultant effect on emissions, as well as the amount of data available on these variables. Finally, the engineering analysis category was concerned with the data available upon which a material balance or related calculation could be made.

Depending on which information categories were employed to develop it, each set of factors was assigned a numerical score, ranging from 5 to 40. For example, if the factors developed for a certain process were based on a large number of source tests, a moderate amount of process data, and no engineering analysis work, the assigned score would be 20 + 5 = 25.

Each numerical score was, in turn, converted to a letter rank as follows:

Numerical Rank	*Letter Rank*
5 or less	E (Poor)
6 to 15	D (Below average)
16 to 25	C (Average)
26 to 35	B (Above average)
36 to 40	A (Excellent)

These rankings are presented below the table titles throughout this publication.

The reader must be herein cautioned not to use these emission factors indiscriminately. That is, the factors generally will not permit the calculation of accurate emissions measurements from an individual installation. Only an on-site source test can provide data sufficiently accurate and precise to use in such undertakings as the design and purchase of control equipment or the initiation of a legal action. Factors are more valid when applied to a large number of processes, as, for example, when emission inventories are conducted as part of community or nationwide air pollution studies.

1. EXTERNAL COMBUSTION SOURCES

External combustion sources include steam-electric generating plants, industrial boilers, commercial and institutional boilers, and commercial and domestic combustion units. Coal, fuel oil, and natural gas are the major fossil fuels used by these sources. Other fuels used in relatively small quantities are liquefied petroleum gas, wood, coke, refinery gas, blast furnace gas, and other waste or by-product fuels. Coal, oil, and natural gas currently supply about 95 percent of the total thermal energy consumed in the United States. In 1970 over 500 million tons (454×10^6 MT) of coal, 623 million barrels (99×10^9 liters) of distillate fuel oil, 715 million barrels (114×10^9 liters) of residual fuel oil, and 22 trillion cubic feet (623×10^{12} liters) of natural gas were consumed in the United States.[1]

Power generation, process heating, and space heating are some of the largest fuel-combustion sources of sulfur oxides, nitrogen oxides, and particulate emissions. The following sections present emission factor data for the major fossil fuels – coal, fuel oil, and natural gas – as well as for liquefied petroleum gas and wood waste combustion in boilers.

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1.1 BITUMINOUS COAL COMBUSTION

Revised by Robert Rosensteel
and Thomas Lahre

1.1.1 General

Coal, the most abundant fossil fuel in the United States, is burned in a wide variety of furnaces to produce heat and steam. Coal-fired furnaces range in size from small handfired units with capacities of 10 to 20 pounds (4.5 to 9 kilograms) of coal per hour to large pulverized-coal-fired units, which may burn 300 to 400 tons (275 to 360 MT) of coal per hour.

Although predominantly carbon, coal contains many compounds in varying amounts. The exact nature and quantity of these compounds are determined by the location of the mine producing the coal and will usually effect the final use of the coal.

1.1.2 Emissions and Controls

1.1.2.1 Particulates[1]. – Particulates emitted from coal combustion consist primarily of carbon, silica, alumina, and iron oxide in the fly-ash. The quantity of atmospheric particulate emissions is dependent upon the type of combustion unit in which the coal is burned, the ash content of the coal, and the type of control equipment used.

Table 1.1-1 gives the range of collection efficiencies for common types of fly-ash control equipment. Particulate emission factors expressed as pounds of particulate per ton of coal burned are presented in Table 1.1-2.

1.1.2.2 Sulfur Oxides[1,2] - Factors for uncontrolled sulfur oxides emission are shown in Table 1-2 along with factors for other gases emitted. The emission factor for sulfur oxides indicates a conversion of 95 percent of the available sulfur to sulfur oxide. The balance of the sulfur is emitted in the fly-ash or combines with the slag or ash in the furnace and is removed with them.[1] Increased attention has been given to the control of sulfur oxide emissions from the combustion of coal. The use of low-sulfur coal has been recommended in many areas; where low-sulfur coal is not available, other methods in which the focus is on the removal of sulfur oxide from the flue gas before it enters the atmosphere must be given consideration.

A number of flue-gas desulfurization processes have been evaluated; effective methods are undergoing full-scale operation. Processes included in this category are: limestone-dolomite injection, limestone wet scrubbing, catalytic oxidation, magnesium oxide scrubbing, and the Wellman-Lord process. Detailed discussion of various flue-gas desulfurization processes may be found in the literature.[12,13]

1.1.2.3 Nitrogen Oxides[1,3] - Emissions of oxides of nitrogen result not only from the high temperature reaction of atmospheric nitrogen and oxygen in the combustion zone, but also from the partial combustion of nitrogenous compounds contained in the fuel. The important factors that affect NO_x production are: flame and furnace temperature, residence time of combustion gases at the flame temperature, rate of cooling of the gases, and amount of excess air present in the flame. Discussions of the mechanisms involved are contained in the indicated references.

1.1.2.4 Other Gases - The efficiency of combustion primarily determines the carbon monoxide and hydrocarbon content of the gases emitted from bituminous coal combustion. Successful combustion that results in a low level of carbon monoxide and organic emissions requires a high degree of turbulence, a high temperature, and sufficient time for the combustion reaction to take place. Thus, careful control of excess air rates, the use of high combustion temperature, and provision for intimate fuel-air contact will minimize these emissions.

Factors for these gaseous emissions are also presented in Table 1.1-2. The size range in Btu per hour for the various types of furnaces as shown in Table 1.1-2 is only provided as a guide in selecting the proper factor and is not meant to distinguish clearly between furnace applications.

TABLE 1.1-1. RANGE OF COLLECTION EFFICIENCIES FOR COMMON TYPES OF FLY-ASH CONTROL EQUIPMENT[a]

Type of furnace	Range of collection efficiencies, %			
	Electrostatic precipitator	High efficiency cyclone	Low-resistance cyclone	Settling chamber expanded chimney bases
Cyclone furnace	65 to 99.5[b]	30 to 40	20 to 30	10[b]
Pulverized unit	80 to 99.5[b]	65 to 75	40 to 60	20[b]
Spreader stoker	99.5[b]	85 to 90	70 to 80	20[b] to 30
Other stokers	99.5[b]	90 to 95	75 to 85	25 to 50

[a] References 1 and 2.

[b] The maximum efficiency to be expected for this collection device applied to this type source.

Table 1.1-2. EMISSION FACTORS FOR BITUMINOUS COAL COMBUSTION WITHOUT CONTROL EQUIPMENT
EMISSION FACTOR RATING: A

Furnace size, 10^6 Btu/hr heat input[a]	Particulates[b]		Sulfur oxides[c]		Carbon monoxide		Hydro-carbons[d]		Nitrogen oxides		Aldehydes	
	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned
Greater than 100[e] (Utility and large industrial boilers)												
Pulverized												
General	16A	8A	38S	19S	1	0.5	0.3	0.15	18	9	0.005	0.0025
Wet bottom	13A[f]	6.5A	38S	19S	1	0.5	0.3	0.15	30	15	0.005	0.0025
Dry bottom	17A	8.5A	38S	19S	1	0.5	0.3	0.15	18	9	0.005	0.0025
Cyclone	2A	1A	38S	19S	1	0.5	0.3	0.15	55	27.5	0.005	0.0025
10 to 100[g] (large commercial and general industrial boilers)												
Spreader stoker[h]	13A[i]	6.5A	38S	19S	2	1	1	0.5	15	7.5	0.005	0.0025
Less than 10[j] (commercial and domestic furnaces)												
Spreader stoker	2A	1A	38S	19S	10	5	3	1.5	6	3	0.005	0.0025
Hand-fired units	20	10	38S	19S	90	45	20	10	3	1.5	0.005	0.0025

[a] 1 Btu/hr = 0.252 kcal/hr.

[b] The letter A on all units other than hand-fired equipment indicates that the weight percentage of ash in the coal should be multiplied by the value given. Example: If the factor is 16 and the ash content is 10 percent, the particulate emissions before the control equipment would be 10 times 16, or 160 pounds of particulate per ton of coal (10 times 8, or 80 kg of particulates per MT of coal).

[c] S equals the sulfur content (see footnote b above).

[d] Expressed as methane.

[e] References 1 and 2 through 7.

[f] Without fly-ash reinjection.

[g] References 1, 4, and 7 through 9.

[h] For all other stokers use 5A for particulate emission factor.

[i] Without fly-ash reinjection. With fly-ash reinjection use 20A. This value is not an emission factor but represents loading reaching the control equipment.

[j] References 1, 3, and 10.

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1.2 ANTHRACITE COAL COMBUSTION

Revised by Robert Rosensteel

1.2.1 General[1]

Because of its low volatile content and the nonclinkering characteristics of its ash, anthracite coal is used in medium-sized industrial and institutional boilers with stationary or traveling grates. Although it is not used in spreader stokers because of its low volatile content and relatively high ignition temperature, anthracite coal may be burned in pulverized-coal-fired units, but this practice is limited to only a few plants in Eastern Pennsylvania because of ignition difficulties. Anthracite coal has also been widely used in hand-fired furnaces.

1.2.2 Emissions and Controls[1]

Particulate emissions from anthracite coal combustion are greatly affected by the rate of firing and by the ash content of the fuel. Smoke emissions from anthracite coal combustion are rarely a problem. High grate loadings result in excessive emissions because of the underfire air required to burn the fuel. Large units equipped with forced-draft fans may also produce high rates of particulate emissions. Hand-fired furnaces and some small natural-draft units have fewer particulate emissions because underfire air is not usually supplied by mechanical means.

The quantity of sulfur dioxide emissions from coal combustion, as from other fuels, is directly related to the sulfur content of the coal. Nitrogen oxide and carbon monoxide emissions are similar to those found in bituminous-coal-fired units because excess air rates and combustion temperatures are similar. Because the volatile matter content of anthracite is lower than that of bituminous, hydrocarbon emissions from combustion of anthracite are somewhat lower than those from bituminous coal combustion.

The factors for uncontrolled emissions from anthracite coal combustion are presented in Table 1.2-1.

Table 1.2-1. EMISSIONS FROM ANTHRACITE COAL COMBUSTION WITHOUT CONTROL EQUIPMENT
EMISSION FACTOR RATING: B

Type of furnace	Particulate[a,b]		Sulfur dioxide[c]		Sulfur trioxide[c,d]		Hydrocarbons[e,f]		Carbon monoxide[g]		Nitrogen oxides[e,h]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Pulverized (dry bottom), no fly-ash reinjection	17A	8.5A	38S	19S	0.5S	0.25S	0.03	0.015	1	0.5	18	9
Overfeed stokers, no fly-ash reinjection[i]	2A	1A	38S	19S	0.5S	0.25S	0.2	0.1	(2 to 10)[j]	(1 to 5)	(6 to 15)[k]	(3 to 7.5)
Hand-fired units	10	5	38S	19S	0.9S	0.45S	2.5	1.25	90	45	3	1.5

[a] References 2 through 7.

[b] A is the ash content expressed as weight percent.

[c] S is the sulfur content expressed as weight percent.

[d] References 5, 7, and 8.

[e] Based on Reference 2 and bituminous coal combustion.

[f] Expressed as methane.

[g] Based on bituminous coal combustion.

[h] Emitted as NO, but calculated as NO_2.

[i] Based on data obtained from traveling-grate stokers in the 12 to 180 Btu/hr (3 to 45 kcal/hr) heat input range. Anthracite is not burned in spreader stokers.

[j] Use high side of range for smaller-sized units (less than 10×10^6 Btu/hr (2.5×10^6 kcal/hr) heat input).

[k] Use low side of range for smaller-sized units (less than 10×10^6 Btu/hr (2.5×10^6 kcal/hr) heat input).

NOTE: Approximate efficiencies of control devices used for anthracite are: cyclone, 75 to 85 percent, and electrostatic precipitators, 85 percent.

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1.3 FUEL OIL COMBUSTION

Revised by Thomas Lahre

1.3.1 General[1]

Fuel oil is classified into two major types, residual and distillate. Distillate fuel oil is primarily a domestic fuel, but it is used in some commercial and industrial applications where a high-quality oil is required. Fuel oils are classified by grades: grades No. 1 and No. 2, distillate; No. 5 and No. 6, residual; and No. 3 and No. 4, blends. (Grade No. 3 has been practically discontinued.) The primary differences between residual oil and distillate oil are the higher ash and sulfur content of residual oil and the fact that it is much more viscous and therefore harder to burn properly. Residual fuel oils have a heating value of approximately 150,000 Btu/gallon (10,000 kcal/liter); the heating value for distillate oils is about 140,000 Btu/gallon (9,300 kcal/liter).

1.3.2 Emissions

Emissions from oil combustion are dependent on type and size of equipment, method of firing, and maintenance. Table 1.3-1 presents emission factors for fuel oil combustion. Note that the industrial and commercial category is split into residual and distillate because there is a significant difference in particulate emissions from the same equipment, depending on the fuel oil used. It should also be noted that power plants emit less particulate matter per quantity of oil consumed, reportedly because of better design and more precise operation of equipment.

In general, large sources produce more nitrogen oxides than small sources,[1] primarily because of the higher flame and boiler temperatures characteristic of large sources. Large sources, however, emit fewer aldehydes than smaller sources as a result of more complete combustion and higher flame temperatures. Hydrocarbon and carbon monoxide emissions can be kept minimal if proper operating practices are employed; however, as the data suggest, this control is more often accomplished in larger equipment.

Table 1.3-1. EMISSION FACTORS FOR FUEL OIL COMBUSTION
EMISSION FACTOR RATING: A

Pollutant	Type of unit							
			Industrial and commercial					
	Power plant		Residual		Distillate		Domestic	
	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters
Particulate[a]	8	1	23	2.75	15	1.8	10	1.2
Sulfur dioxide[b,c]	157S	19S	157S	19S	142S	17S	142S	17S
Sulfur trioxide[b,c]	2S	0.25S	2S	0.25S	2S	0.25S	2S	0.25S
Carbon monoxide[d]	3	0.4	4	0.5	4	0.5	5	0.6
Hydrocarbons[e]	2	0.25	3	0.35	3	0.35	3	0.35
Nitrogen oxides (NO_2)[f]	105[g]	12.6[g]	(40 to 80)[h]	(4.8 to 9.6)[h]	(40 to 80)[h]	(4.8 to 9.6)[h]	12	1.5
Aldehydes (HCHO)[i]	1	0.12	1	0.12	2	0.25	2	0.25

[a] References 2 through 6.

[b] Reference 2.

[c] S equals percent by weight of sulfur in the oil.

[d] References 2, 7 through 10, 12, and 15.

[e] References 2, 8, and 9 through 12.

[f] References 2 through 6, 8, 10, 12, 13, 15, and 16.

[g] Use 50(6.0) for tangentially fired units.

[h] Use 40 (4.8) for tangentially fired units and 80 (9.6) for horizontally fired units.

[i] References 2, 8, 11, and 14.

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1.4 NATURAL GAS COMBUSTION

Revised by Thomas Lahre

1.4.1 General[1,2]

Natural gas has become one of the major fuels used throughout the country. It is used mainly for power generation, for industrial process steam and heat production, and for domestic and commercial space heating. The primary component of natural gas is methane, although varying amounts of ethane and smaller amounts of nitrogen, helium, and carbon dioxide are also present. The average gross heating value of natural gas is approximately 1050 Btu/stdft^3 (9350 kcal/Nm^3), varying generally between 1000 and 1100 Btu/stdft^3 (8900 to 9800 kcal/Nm^3).

Because natural gas in its original state is a gaseous, homogenous fluid, its combustion is simple and can be precisely controlled. Common excess air rates range from 10 to 15 percent; however, some large units operate at excess air rates as low as 5 percent to maximize efficiency and minimize nitrogen oxide (NO_x) emissions.

1.4.2 Emissions and Controls[3-16]

Even though natural gas is considered to be a relatively clean fuel, some emissions can occur from the combustion reaction. For example, improper operating conditions, including poor mixing, insufficient air, etc., may cause large amounts of smoke, carbon monoxide, and hydrocarbons to be produced. Moreover, because a sulfur-containing mercaptan is added to natural gas for detection purposes, small amounts of sulfur oxides will also be produced in the combustion process.

Nitrogen oxides are the major pollutants of concern when burning natural gas. Nitrogen oxide emissions are a function of the temperature in the combustion chamber and the rate of cooling of the combustion products. Emission levels generally vary considerably with the type and size of unit and are also a function of loading.

In some large boilers, several operating modifications have been employed for NO_x control. Staged combustion, for example, including off-stoichiometric firing and/or two-stage combustion, can reduce NO_x emissions by 30 to 70 percent. In off-stoichiometric firing, also called "biased firing," some burners are operated fuel-rich, some fuel-lean, while others may supply air only. In two-staged combustion, the burners are operated fuel-rich (by introducing only 80 to 95 percent stoichiometric air) with combustion being completed by air injected above the flame zone through second-stage "NO-ports." In staged combustion, NO_x emissions are reduced because the bulk of combustion occurs under fuel-rich, reducing conditions.

Other NO_x-reducing modifications include low excess air firing and flue gas recirculation. In low excess air firing, excess air levels are kept as low as possible without producing unacceptable levels of unburned combustibles (carbon monoxide, hydrocarbons, and smoke) and/or other operational problems. This technique can reduce NO_x emissions by 10 to 30 percent primarily because of the lack of availability of oxygen during combustion. Flue gas recirculation into the primary combustion zone, because the flue gas is relatively cool and oxygen deficient, can also lower NO_x emissions by 20 to 60 percent depending on the amount of gas recirculated. At present only a few systems have this capability, however.

Combinations of the above combustion modifications may also be employed to further reduce NO_x emissions. In some boilers, for instance, NO_x reductions as high as 70 to 90 percent have been produced as a result of employing several of these techniques simultaneously. In general, however, because the net effect of any of these combinations varies greatly, it is difficult to predict what the overall reductions will be in any given unit.

Emission factors for natural gas combustion are presented in Table 1.4-1. Flue gas cleaning equipment has not been utilized to control emissions from natural gas combustion equipment.

Table 1.4-1. EMISSION FACTORS FOR NATURAL GAS COMBUSTION
EMISSION FACTOR RATING: A

	Type of unit					
	Power plant		Industrial process boiler		Domestic and commercial heating	
Pollutant	lb/10^6 ft^3	kg/10^6 m^3	lb/10^6 ft^3	kg/10^6 m^3	lb/10^6 ft^3	kg/10^6 m^3
Particulates[a]	5-15	80-240	5-15	80-240	5-15	80-240
Sulfur oxides (SO_2)[b]	0.6	9.6	0.6	9.6	0.6	9.6
Carbon monoxide[c]	17	272	17	272	20	320
Hydrocarbons (as CH_4)[d]	1	16	3	48	8	128
Nitrogen oxides (NO_2)[e]	700[f,h]	11,200[f,h]	(120-230)[i]	(1920-3680)[i]	(80-120)[j]	(1280-1920)[j]

[a] References 4,7,8,12.

[b] Reference 4 (based on an average sulfur content of natural gas of 2000 gr/10^6 stdft^3 (4600 g/10^6 Nm^3).

[c] References 5, 8-12.

[d] References 8, 9, 12.

[e] References 3-9, 12-15.

[f] Use 300 lb/10^6 stdft^3 (4800 kg/10^6 Nm^3) for tangentially fired units.

[g] At reduced loads, multiply this factor by the load reduction coefficient given in Figure 1.4-1.

[h] See text for potential NO_x reductions due to combustion modifications. Note that the NO_x reduction from these modifications will also occur at reduced load conditions.

[i] This represents a typical range for many industrial boilers. For large industrial units (> 100 MMBtu/hr) use the NO_x factors presented for power plants.

[j] Use 80 (1280) for domestic heating units and 120 (1920) for commercial units.

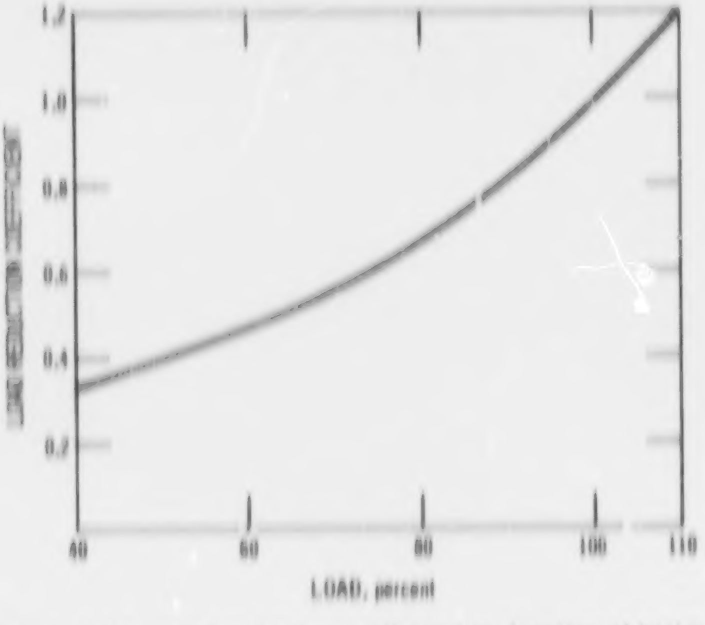

Figure 1.4-1. Load reduction coefficient as function of boiler load. (Used to determine NO_x reductions at reduced loads in large boilers.)

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1.5 LIQUEFIED PETROLEUM GAS CONSUMPTION

Revised by Thomas Lahre

1.5.1 General[1]

Liquefied petroleum gas, commonly referred to as LPG, consists mainly of butane, propane, or a mixture of the two, and of trace amounts of propylene and butylene. This gas, obtained from oil or gas wells as a by-product of gasoline refining, is sold as a liquid in metal cylinders under pressure and, therefore, is often called bottled gas. LPG is graded according to maximum vapor pressure with Grade A being predominantly butane, Grade F being predominantly propane, and Grades B through E consisting of varying mixtures of butane and propane. The heating value of LPG ranges from 97,400 Btu/gallon (6,480 kcal/liter) for Grade A to 90,500 Btu/gallon (6,030 kcal/liter) for Grade F. The largest market for LPG is the domestic-commercial market, followed by the chemical industry and the internal combustion engine.

1.5.2 Emissions[1]

LPG is considered a "clean" fuel because it does not produce visible emissions. Gaseous pollutants such as carbon monoxide, hydrocarbons, and nitrogen oxides do occur, however. The most significant factors affecting these emissions are the burner design, adjustment, and venting.[2] Improper design, blocking and clogging of the flue vent, and lack of combustion air result in improper combustion that causes the emission of aldehydes, carbon monoxide, hydrocarbons, and other organics. Nitrogen oxide emissions are a function of a number of variables including temperature, excess air, and residence time in the combustion zone. The amount of sulfur dioxide emitted is directly proportional to the amount of sulfur in the fuel. Emission factors for LPG combustion are presented in Table 1.5-1.

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Table 1.5-1. EMISSION FACTORS FOR LPG COMBUSTION[a]

EMISSION FACTOR RATING: C

Pollutant	Industrial process furnaces				Domestic and commercial furnaces			
	Butane		Propane		Butane		Propane	
	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters
Particulates	1.8	0.22	1.7	0.20	1.9	0.23	1.8	0.22
Sulfur oxides[b]	0.09S	0.011S	0.09S	0.011S	0.09S	0.011S	0.09S	0.011S
Carbon monoxide	1.6	0.19	1.5	0.18	2.0	0.24	1.9	0.23
Hydrocarbons	0.3	0.036	0.3	0.036	0.8	0.096	0.7	0.084
Nitrogen oxides[c]	12.1	1.45	11.2	1.35	8 to 12[d]	1.0 to 1.5[d]	7 to 11[d]	0.8 to 1.3[d]

[a] LPG emission factors calculated assuming emissions (excluding sulfur oxides) are the same, on a heat input basis, as for natural gas combustion.

[b] S equals the sulfur content expressed in grains per 100 ft^3 gas vapor; e.g., if the sulfur content is 0.16 grain per 100 ft^3 (0.366 g/100 m^3) vapor, the SO_2 emission factor would be (0.09 x 0.16) or 0.014 lb SO_2 per 1000 gallons (0.011 x 0.366) or 0.0040 kg SO_2/10^3 liters) butane burned.

[c] Expressed as NO_2.

[d] Use lower value for domestic units and higher value for commercial units.

1.6 WOOD/BARK WASTE COMBUSTION IN BOILERS

Revised by Thomas Lahre

1.6.1 General [1-3]

Today, the burning of wood/bark waste in boilers is largely confined to those industries where it is available as a by-product. It is burned both to recover heat energy and to alleviate a potential solid waste disposal problem. Wood/bark waste may include large pieces such as slabs, logs, and bark strips as well as smaller pieces such as ends, shavings, and sawdust. Heating values for this waste range from 8000 to 9000 Btu/lb, on a dry basis; however, because of typical moisture contents of 40 to 75 percent, the as-fired heating values for many wood/bark waste materials range as low as 4000 to 6000 Btu/lb. Generally, bark is the major type of waste burned in pulp mills; whereas, a variable mixture of wood and bark waste, or wood waste alone, is most frequently burned in the lumber, furniture, and plywood industries.

1.6.2 Firing Practices[1-3]

A variety of boiler firing configurations are utilized for burning wood/bark waste. One common type in smaller operations is the Dutch Oven, or extension type of furnace with a flat grate. In this unit the fuel is fed through the furnace roof and burned in a cone-shaped pile on the grate. In many other, generally larger, operations, more conventional boilers have been modified to burn wood/bark waste. These units may include spreader stokers with traveling grates, vibrating grate stokers, etc., as well as tangentially fired or cyclone fired boilers. Generally, an auxiliary fuel is burned in these units to maintain constant steam when the waste fuel supply fluctuates and/or to provide more steam than is possible from the waste supply alone.

1.6.3 Emissions [1,2,4-8]

The major pollutant of concern from wood/bark boilers is particulate matter although other pollutants, particularly carbon monoxide, may be emitted in significant amounts under poor operating conditions. These emissions depend on a number of variables including (1) the composition of the waste fuel burned, (2) the degree of fly-ash reinjection employed, and (3) furnace design and operating conditions.

The composition of wood/bark waste depends largely on the industry from whence it originates. Pulping operations, for instance, produce great quantities of bark that may contain more than 70 percent moisture (by weight) as well as high levels of sand and other noncombustibles. Because of this, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well controlled. On the other hand, some operations such as furniture manufacture, produce a clean, dry (5 to 50 percent moisture) wood waste that results in relatively few particulate emissions when properly burned. Still other operations, such as sawmills, burn a variable mixture of bark and wood waste that results in particulate emissions somewhere in between these two extremes.

Fly-ash reinjection, which is commonly employed in many larger boilers to improve fuel-use efficiency, has a considerable effect on particulate emissions. Because a fraction of the collected fly-ash is reinjected into the boiler, the dust loading from the furnace, and consequently from the collection device, increases significantly per ton of wood waste burned. It is reported that full reinjection can cause a 10-fold increase in the dust loadings of some systems although increases of 1.2 to 2 times are more typical for boilers employing 50 to 100 percent reinjection. A major factor affecting this dust loading increase is the extent to which the sand and other non-combustibles can be successfully separated from the fly-ash before reinjection to the furnace.

Furnace design and operating conditions are particularly important when burning wood and bark waste. For example, because of the high moisture content in this waste, a larger area of refractory surface should be provided to dry the fuel prior to combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist or when sufficient secondary air is not available, the combustion temperature is lowered, incomplete combustion occurs, and increased particulate, carbon monoxide, and hydrocarbon emissions will result.

Emission factors for wood waste boilers are presented in Table 1.6-1. For boilers where fly-ash reinjection is employed, two factors are shown: the first represents the dust loading reaching the control equipment; the value in parenthesis represents the dust loading after controls assuming about 80 percent control efficiency. All other factors represent uncontrolled emissions.

Table 1.6-1. EMISSION FACTORS FOR WOOD AND BARK WASTE COMBUSTION IN BOILERS
EMISSION FACTOR RATING: B

Pollutant	Emissions	
	lb/ton	kg/MT
Particulates[a]		
Bark[b,c]		
With fly-ash reinjection[d]	75 (15)	37.5 (7.5)
Without fly-ash reinjection	50	25
Wood/bark mixture[b,e]		
With fly-ash reinjection[d]	45 (9)	22.5 (4.5)
Without fly-ash reinjection	30	15
Wood[f,g]	5-15	2.5-7.5
Sulfur oxides (SO_2)[h,i]	1.5	0.75
Carbon monoxide[j]	2-60	1-30
Hydrocarbons[k]	2-70	1-35
Nitrogen oxides (NO_2)[l]	10	5

[a] These emission factors were determined for boilers burning gas or oil as an auxiliary fuel, and it was assumed all particulates resulted from the waste fuel alone. When coal is burned as an auxiliary fuel, the appropriate emission factor from Table 1.1-2 should be used in addition to the above factor.

[b] These factors based on an as-fired moisture content of 50 percent.

[c] References 2, 4, 9.

[d] This factor represents a typical dust loading reaching the control equipment for boilers employing fly-ash reinjection. The value in parenthesis represents emissions after the control equipment assuming an average efficiency of 80 percent.

[e] References 7, 10.

[f] This waste includes clean, dry (5 to 50 percent moisture) sawdust, shavings, ends, etc., and no bark. For well designed and operated boilers use lower value and higher values for others. This factor is expressed on an as-fired moisture content basis assuming no fly-ash reinjection.

[g] References 11-13.

[h] This factor is calculated by material balance assuming a maximum sulfur content of 0.1 percent in the waste. When auxiliary fuels are burned, the appropriate factors from Tables 1.1-2, 1.3-1, or 1.4-1 should be used in addition to determine sulfur oxide emissions.

[i] References 1, 5, 7.

[j] This factor is based on engineering judgment and limited data from references 11 through 13. Use lower values for well designed and operated boilers.

[k] This factor is based on limited data from references 13 through 15. Use lower values for well designed and operated boilers.

[l] Reference 16.

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1.7 LIGNITE COMBUSTION

by Thomas Lahre

1.7.1 General[1-4]

Lignite is a geologically young coal whose properties are intermediate to those of bituminous coal and peat. It has a high moisture content (35 to 40 percent, by weight) and a low heating value (6000 to 7500 Btu/lb, wet basis) and is generally only burned close to where it is mined, that is, in the midwestern States centered about North Dakota and in Texas. Although a small amount is used in industrial and domestic situations, lignite is mainly used for steam-electric production in power plants. In the past, lignite was mainly burned in small stokers; today the trend is toward use in much larger pulverized-coal-fired or cyclone-fired boilers.

The major advantage to firing lignite is that, in certain geographical areas, it is plentiful, relatively low in cost, and low in sulfur content (0.4 to 1 percent by weight, wet basis). Disadvantages are that more fuel and larger facilities are necessary to generate each megawatt of power than is the case with bituminous coal. There are several reasons for this. First, the higher moisture content of lignite means that more energy is lost in the gaseous products of combustion, which reduces boiler efficiency. Second, more energy is required to grind lignite to the specified size needed for combustion, especially in pulverized coal-fired units. Third, greater tube spacing and additional soot blowing are required because of the higher ash-fouling tendencies of lignite. Fourth, because of its lower heating value, more fuel must be handled to produce a given amount of power because lignite is not generally cleaned or dried prior to combustion (except for some drying that may occur in the crusher or pulverizer and during subsequent transfer to the burner). Generally, no major problems exist with the handling or combustion of lignite when its unique characteristics are taken into account.

1.7.2 Emissions and Controls[3-8]

The major pollutants of concern when firing lignite, as with any coal, are particulates, sulfur oxides, and nitrogen oxides. Hydrocarbon and carbon monoxide emissions are usually quite low under normal operating conditions.

Particulate emissions appear most dependent on the firing configuration in the boiler. Pulverized-coal-fired units and spreader stokers, which fire all or much of the lignite in suspension, emit the greatest quantity of flyash per unit of fuel burned. Both cyclones, which collect much of the ash as molten slag in the furnace itself, and stokers (other than spreader stokers), which retain a large fraction of the ash in the fuel bed, emit less particulate matter. In general, the higher sodium content of lignite, relative to other coals, lowers particulate emissions by causing much of the resulting flyash to deposit on the boiler tubes. This is especially the case in pulverized-coal-fired units wherein a high fraction of the ash is suspended in the combustion gases and can readily come into contact with the boiler surfaces.

Nitrogen oxides emissions are mainly a function of the boiler firing configuration and excess air. Cyclones produce the highest NO_x levels, primarily because of the high heat-release rates and temperatures reached in the small furnace sections of the boiler. Pulverized-coal-fired boilers produce less NO_x than cyclones because combustion occurs over a larger volume, which results in lower peak flame temperatures. Tangentially fired boilers produce the lowest NO_x levels in this category. Stokers produce the lowest NO_x levels mainly because most existing units are much smaller than the other firing types. In most boilers, regardless of firing configuration, lower excess air during combustion results in lower NO_x emissions.

Sulfur oxide emissions are a function of the alkali (especially sodium) content of the lignite ash. Unlike most fossil fuel combustion, in which over 90 percent of the fuel sulfur is emitted as SO_2, a significant fraction of the sulfur in lignite reacts with the ash components during combustion and is retained in the boiler ash deposits and flyash. Tests have shown that less than 50 percent of the available sulfur may be emitted as SO_2 when a high-sodium lignite is burned, whereas, more than 90 percent may be emitted with low-sodium lignite. As a rough average, about 75 percent of the fuel sulfur will be emitted as SO_2, with the remainder being converted to various sulfate salts.

Air pollution controls on lignite-fired boilers in the United States have mainly been limited to cyclone collectors, which typically achieve 60 to 75 percent collection efficiency on lignite flyash. Electrostatic precipitators, which are widely utilized in Europe on lignitic coals and can effect 99+ percent particulate control, have seen only limited application in the United States to date although their use will probably become widespread on newer units in the future.

Nitrogen oxides reduction (up to 40 percent) has been demonstrated using low excess air firing and staged combustion (see section 1.4 for a discussion of these techniques); it is not yet known, however, whether these techniques can be continuously employed on lignite combustion units without incurring operational problems. Sulfur oxides reduction (up to 50 percent) and some particulate control can be achieved through the use of high sodium lignite. This is not generally considered a desirable practice, however, because of the increased ash fouling that may result.

Emission factors for lignite combustion are presented in Table 1.7-1.

Table 1.7-1. EMISSIONS FROM LIGNITE COMBUSTION WITHOUT CONTROL EQUIPMENT[a]
EMISSION FACTOR RATING: B

	Type of boiler							
	Pulverized coal		Cyclone		Spreader stoker		Other stokers	
Pollutant	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Particulate[b]	7.0A[c]	3.5A[c]	6A	3A	7.0A[d]	3.5A[d]	3.0A	1.5A
Sulfur oxides[e]	30S	15S	30S	15S	30S	15S	30S	15S
Nitrogen oxides[f]	14(8)[g,h]	7(4)[g,h]	17	8.5	6	3	6	3
Hydrocarbons[i]	<1.0	<0.5	<1.0	<0.5	1.0	0.5	1.0	0.5
Carbon monoxide[i]	1.0	0.5	1.0	0.5	2	1	2	1

[a] All emission factors are expressed in terms of pounds of pollutant per ton (kilograms of pollutant per metric ton) of lignite burned, wet basis (35 to 40 percent moisture, by weight).

[b] A is the ash content of the lignite by weight, wet basis. Factors based on References 5 and 6.

[c] This factor is based on data for dry bottom, pulverized-coal-fired units only. It is expected that this factor would be lower for wet bottom units.

[d] Limited data preclude any determination of the effect of flyash reinjection. It is expected that particulate emissions would be greater when reinjection is employed.

[e] S is the sulfur content of the lignite by weight, wet basis. For a high sodium-ash lignite (Na_2O > 8 percent) use 17S lb/ton (8.5S kg/MT); for a low sodium-ash lignite (Na_2O < 2 percent), use 35S lb/ton (17.5S kg/MT). For intermediate sodium-ash lignite, or when the sodium-ash content is unknown, use 30S lb/ton (15S kg/MT). Factors based on References 2, 5, and 6.

[f] Expressed as NO_2. Factors based on References 2, 3, 5, 7, and 8.

[g] Use 14 lb/ton (7 kg/MT) for front-wall-fired and horizontally opposed wall-fired units and 8 lb/ton (4 kg/MT) for tangentially fired units.

[h] Nitrogen oxide emissions may be reduced by 20 to 40 percent with low excess air firing and/or staged combustion in front-fired and opposed-wall-fired units and cyclones.

[i] These factors are based on the similarity of lignite combustion to bituminous coal combustion and on limited data in Reference 7.

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2. SOLID WASTE DISPOSAL

Revised by Robert Rosensteel

As defined in the Solid Waste Disposal Act of 1965, the term "solid waste" means garbage, refuse, and other discarded solid materials, including solid-waste materials resulting from industrial, commercial, and agricultural operations, and from community activities. It includes both combustibles and noncombustibles.

Solid wastes may be classified into four general categories: urban, industrial, mineral, and agricultural. Although urban wastes represent only a relatively small part of the total solid wastes produced, this category has a large potential for air pollution since in heavily populated areas solid waste is often burned to reduce the bulk of material requiring final disposal.[1] The following discussion will be limited to the urban and industrial waste categories.

An average of 5.5 pounds (2.5 kilograms) of urban refuse and garbage is collected per capita per day in the United States.[2] This figure does not include uncollected urban and industrial wastes that are disposed of by other means. Together, uncollected urban and industrial wastes contribute at least 4.5 pounds (2.0 kilograms) per capita per day. The total gives a conservative per capita generation rate of 10 pounds (4.5 kilograms) per day of urban and industrial wastes. Approximately 50 percent of all the urban and industrial waste generated in the United States is burned, using a wide variety of combustion methods with both enclosed and open burning[3]. Atmospheric emissions, both gaseous and particulate, result from refuse disposal operations that use combustion to reduce the quantity of refuse. Emissions from these combustion processes cover a wide range because of their dependence upon the refuse burned, the method of combustion or incineration, and other factors. Because of the large number of variables involved, it is not possible, in general, to delineate when a higher or lower emission factor, or an intermediate value should be used. For this reason, an average emission factor has been presented.

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2.1 REFUSE INCINERATION

Revised by Robert Rosensteel

2.1.1 Process Description[1-4]

The most common types of incinerators consist of a refractory-lined chamber with a grate upon which refuse is burned. In some newer incinerators water-walled furnaces are used. Combustion products are formed by heating and burning of refuse on the grate. In most cases, since insufficient underfire (undergrate) air is provided to enable complete combustion, additional over-fire air is admitted above the burning waste to promote complete gas-phase combustion. In multiple-chamber incinerators, gases from the primary chamber flow to a small secondary mixing chamber where more air is admitted, and more complete oxidation occurs. As much as 300 percent excess air may be supplied in order to promote oxidation of combustibles. Auxiliary burners are sometimes installed in the mixing chamber to increase the combustion temperature. Many small-size incinerators are single-chamber units in which gases are vented from the primary combustion chamber directly into the exhaust stack. Single-chamber incinerators of this type do not meet modern air pollution codes.

2.1.2 Definitions of Incinerator Categories[1]

No exact definitions of incinerator size categories exist, but for this report the following general categories and descriptions have been selected:

1. *Municipal incinerators* - Multiple-chamber units often have capacities greater than 50 tons (45.3 MT) per day and are usually equipped with automatic charging mechanisms, temperature controls, and movable grate systems. Municipal incinerators are also usually equipped with some type of particulate control device, such as a spray chamber or electrostatic precipitator.

2. *Industrial/commercial incinerators* - The capacities of these units cover a wide range, generally between 50 and 4,000 pounds (22.7 and 1,800 kilograms) per hour. Of either single- or multiple-chamber design, these units are often manually charged and intermittently operated. Some industrial incinerators are similar to municipal incinerators in size and design. Better designed emission control systems include gas-fired afterburners or scrubbing, or both.

3. *Trench Incinerators* - A trench incinerator is designed for the combustion of wastes having relatively high heat content and low ash content. The design of the unit is simple: a U-shaped combustion chamber is formed by the sides and bottom of the pit and air is supplied from nozzles along the top of the pit. The nozzles are directed at an angle below the horizontal to provide a curtain of air across the top of the pit and to provide air for combustion in the pit. The trench incinerator is not as efficient for burning wastes as the municipal multiple-chamber unit, except where careful precautions are taken to use it for disposal of low-ash, high-heat-content refuse, and where special attention is paid to proper operation. Low construction and operating costs have resulted in the use of this incinerator to dispose of materials other than those for which it was originally designed. Emission factors for trench incinerators used to burn three such materials[7] are included in Table 2.1-1.

4. *Domestic incinerators* - This category includes incinerators marketed for residential use. Fairly simple in design, they may have single or multiple chambers and usually are equipped with an auxiliary burner to aid combustion.

Table 2.1-1. EMISSION FACTORS FOR REFUSE INCINERATORS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: A

Incinerator type	Particulates		Sulfur oxides[b]		Carbon monoxide		Hydrocarbons[c]		Nitrogen oxides[d]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Municipal[e]										
Multiple chamber, uncontrolled	30	15	2.5	1.25	35	17.5	1.5	0.75	3	1.5
With settling chamber and water spray system[f]	14	7	2.5	1.25	35	17.5	1.5	0.75	3	1.5
Industrial/commercial										
Multiple chamber[g]	7	3.5	2.5[h]	1.25	10	5	3	1.5	3	1.5
Single chamber[i]	15	7.5	2.5[h]	1.25	20	10	15	7.5	2	1
Trench[j]										
Wood	13	6.5	0.1[k]	0.05	NA[l]	NA	NA	NA	4	2
Rubber tires	138	69	NA	NA	NA	NA	NA	NA	NA	NA
Municipal refuse	37	18.5	2.5[h]	1.25	NA	NA	NA	NA	NA	NA
Controlled air[m]	1.4	0.7	1.5	0.75	Neg	Neg	Neg	Neg	10	5
Flue-fed single chamber[n]	30	15	0.5	0.25	20	10	15	7.5	3	1.5
Flue-fed (modified)[o,p]	6	3	0.5	0.25	10	5	3	1.5	10	5
Domestic single chamber										
Without primary burner[q]	35	17.5	0.5	0.25	300	150	100	50	1	0.5
With primary burner[r]	7	3.5	0.5	0.25	Neg	Neg	2	1	2	1
Pathological[s]	8	4	Neg	Neg	Neg	Neg	Neg	Neg	3	1.5

[a] Average factors given based on EPA procedures for incinerator stack testing.

[b] Expressed as sulfur dioxide.

[c] Expressed as methane.

[d] Expressed as nitrogen dioxide.

[e] References 3 and 8 through 14.

[f] Most municipal incinerators are equipped with at least this much control; see Table 2.1-2 for appropriate efficiencies for other controls.

[g] References 3, 5, 10, 13, and 15.

[h] Based on municipal incinerator data.

[i] References 3, 5, 10, and 15.

[j] Reference 7.

[k] Based on data for wood combustion in conical burners.

[l] Not available.

[m] Reference 9.

[n] References 3, 10, 11, 13, 15, and 16.

[o] With afterburners and draft controls.

[p] References 3, 11, and 15.

[q] References 5 and 10.

[r] Reference 5.

[s] References 3 and 9.

5. *Flue-fed incinerators* – These units, commonly found in large apartment houses, are characterized by the charging method of dropping refuse down the incinerator flue and into the combustion chamber. Modified flue-fed incinerators utilize afterburners and draft controls to improve combustion efficiency and reduce emissions.

6. *Pathological incinerators* – These are incinerators used to dispose of animal remains and other organic material of high moisture content. Generally, these units are in a size range of 50 to 100 pounds (22.7 to 45.4 kilograms) per hour. Wastes are burned on a hearth in the combustion chamber. The units are equipped with combustion controls and afterburners to ensure good combustion and minimal emissions.

7. *Controlled air incinerators* – These units operate on a controlled combustion principle in which the waste is burned in the absence of sufficient oxygen for complete combustion in the main chamber. This process generates a highly combustible gas mixture that is then burned with excess air in a secondary chamber, resulting in efficient combustion. These units are usually equipped with automatic charging mechanisms and are characterized by the high effluent temperatures reached at the exit of the incinerators.

2.1.3 Emissions and Controls[1]

Operating conditions, refuse composition, and basic incinerator design have a pronounced effect on emissions. The manner in which air is supplied to the combustion chamber or chambers has, among all the parameters, the greatest effect on the quantity of particulate emissions. Air may be introduced from beneath the chamber, from the side, or from the top of the combustion area. As underfire air is increased, an increase in fly-ash emissions occurs. Erratic refuse charging causes a disruption of the combustion bed and a subsequent release of large quantities of particulates. Large quantities of uncombusted particulate matter and carbon monoxide are also emitted for an extended period after charging of batch-fed units because of interruptions in the combustion process. In continuously fed units, furnace particulate emissions are strongly dependent upon grate type. The use of rotary kiln and reciprocating grates results in higher particulate emissions than the use of rocking or traveling grates.[14] Emissions of oxides of sulfur are dependent on the sulfur content of the refuse. Carbon monoxide and unburned hydrocarbon emissions may be significant and are caused by poor combustion resulting from improper incinerator design or operating conditions. Nitrogen oxide emissions increase with an increase in the temperature of the combustion zone, an increase in the residence time in the combustion zone before quenching, and an increase in the excess air rates to the point where dilution cooling overcomes the effect of increased oxygen concentration.[14]

Table 2.1-2 lists the relative collection efficiencies of particulate control equipment used for municipal incinerators. This control equipment has little effect on gaseous emissions. Table 2.1-1 summarizes the uncontrolled emission factors for the various types of incinerators previously discussed.

Table 2.1-2. COLLECTION EFFICIENCIES FOR VARIOUS TYPES OF MUNICIPAL INCINERATION PARTICULATE CONTROL SYSTEMS[a]

Type of system	Efficiency, %
Settling chamber	0 to 30
Settling chamber and water spray	30 to 60
Wetted baffles	60
Mechanical collector	30 to 80
Scrubber	80 to 95
Electrostatic precipitator	90 to 96
Fabric filter	97 to 99

[a] References 3, 5, 8, and 17 through 21.

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2.2 AUTOMOBILE BODY INCINERATION

Revised by Robert Rosensteel

2.2.1 Process Description

Auto incinerators consist of a single primary combustion chamber in which one or several partially stripped cars are burned. (Tires are removed.) Approximately 30 to 40 minutes is required to burn two bodies simultaneously.[2] As many as 50 cars per day can be burned in this batch-type operation, depending on the capacity of the incinerator. Continuous operations in which cars are placed on a conveyor belt and passed through a tunnel-type incinerator have capacities of more than 50 cars per 8-hour day.

2.2.2 Emissions and Controls[1]

Both the degree of combustion as determined by the incinerator design and the amount of combustible material left on the car greatly affect emissions. Temperatures on the order of 1200°F (650°C) are reached during auto body incineration.[2] This relatively low combustion temperature is a result of the large incinerator volume needed to contain the bodies as compared with the small quantity of combustible material. The use of overfire air jets in the primary combustion chamber increases combustion efficiency by providing air and increased turbulence.

In an attempt to reduce the various air pollutants produced by this method of burning, some auto incinerators are equipped with emission control devices. Afterburners and low-voltage electrostatic precipitators have been used to reduce particulate emissions; the former also reduces some of the gaseous emissions.[3,4] When afterburners are used to control emissions, the temperature in the secondary combustion chamber should be at least 1500°F (815°C). Lower temperatures result in higher emissions. Emission factors for auto body incinerators are presented in Table 2.2-1.

Table 2.2-1. EMISSION FACTORS FOR AUTO BODY INCINERATION[a]
EMISSION FACTOR RATING: B

Pollutants	Uncontrolled		With afterburner	
	lb/car	kg/car	lb/car	kg/car
Particulate[b]	2	0.9	1.5	0.68
Carbon monoxide[c]	2.5	1.1	Neg	Neg
Hydrocarbons (CH_4)[c]	0.5	0.23	Neg	Neg
Nitrogen oxides (NO_2)[d]	0.1	0.05	0.02	0.01
Aldehydes (HCOH)[d]	0.2	0.09	0.06	0.03
Organic acids (acetic)[d]	0.21	0.10	0.07	0.03

[a] Based on 250 lb (113 kg) of combustible material on stripped car body.
[b] References 2 and 4.
[c] Based on data for open burning and References 2 and 5.
[d] Reference 3.

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2.3 CONICAL BURNERS

2.3.1 Process Description[1]

Conical burners are generally a truncated metal cone with a screened top vent. The charge is placed on a raised grate by either conveyor or bulldozer; however, the use of a conveyor results in more efficient burning. No supplemental fuel is used, but combustion air is often supplemented by underfire air blown into the chamber below the grate and by overfire air introduced through peripheral openings in the shell.

2.3.2 Emissions and Controls

The quantities and types of pollutants released from conical burners are dependent on the composition and moisture content of the charged material, control of combustion air, type of charging system used, and the condition in which the incinerator is maintained. The most critical of these factors seems to be the level of maintenance on the incinerators. It is not uncommon for conical burners to have missing doors and numerous holes in the shell, resulting in excessive combustion air, low temperatures, and, therefore, high emission rates of combustible pollutants.[2]

Particulate control systems have been adapted to conical burners with some success. These control systems include water curtains (wet caps) and water scrubbers. Emission factors for conical burners are shown in Table 2.3-1.

Table 2.3-1. EMISSION FACTORS FOR WASTE INCINERATION IN CONICAL BURNERS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: B

Type of waste	Particulates		Sulfur oxides		Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Municipal refuse[b]	20(10 to 60)[c,d]	10	2	1	60	30	20	10	5	2.5
Wood refuse[e]	1[f] 7[g] 20[h]	0.5 3.5 10	0.1	0.05	130	65	11	5.5	1	0.5

[a] Moisture content as fired is approximately 50 percent for wood waste.

[b] Except for particulates, factors are based on comparison with other waste disposal practices.

[c] Use high side of range for intermittent operations charged with a bulldozer.

[d] Based on Reference 3.

[e] References 4 through 9.

[f] Satisfactory operation: properly maintained burner with adjustable underfire air supply and adjustable, tangential overfire air inlets, approximately 500 percent excess air and 700°F (370°C) exit gas temperature.

[g] Unsatisfactory operation: properly maintained burner with radial overfire air supply near bottom of shell, approximately 1200 percent excess air and 400°F (204°C) exit gas temperature.

[h] Very unsatisfactory operation: improperly maintained burner with radial overfire air supply near bottom of shell and many gaping holes in shell, approximately 1500 percent excess air and 400°F (204°C) exit gas temperature.

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2.4 OPEN BURNING

2.4.1 General[1]

Open burning can be done in open drums or baskets and in large-scale open dumps or pits. Materials commonly disposed of in this manner are municipal waste, auto body components, landscape refuse, agricultural field refuse, wood refuse, and bulky industrial refuse.

2.4.2 Emissions

Ground-level open burning is affected by many variables including wind, ambient temperature, composition and moisture content of the debris burned, size and shape of the debris burned, and compactness of the pile. In general, the relatively low temperatures associated with open burning increase the emission of particulates, carbon monoxide, and hydrocarbons and suppress the emission of nitrogen oxides. Sulfur oxide emissions are a direct function of the sulfur content of the refuse. Emission factors are presented in Table 2.4-1 for the open burning of three broad categories of waste: municipal refuse, automobile components, and horticultural refuse.

Table 2.4-1. EMISSION FACTORS FOR OPEN BURNING
EMISSION FACTOR RATING: B

Pollutant	Municipal refuse[a]	Automobile components[b,c]	Agricultural field burning[d]	Landscape refuse and pruning[d]	Wood[d] refuse
Particulates					
lb/ton	16	100	17	17	17
kg/MT	8	50	8.5	8.5	8.5
Sulfur oxides					
lb/ton	1	Neg	Neg	Neg	Neg
kg/MT	0.5	Neg	Neg	Neg	Neg
Carbon monoxide					
lb/ton	85	125	100	60	50
kg/MT	42.5	62.5	50	30	25
Hydrocarbons (CH_4)					
lb/ton	30	30	20	20	4
kg/MT	15	15	10	10	2
Nitrogen oxides					
lb/ton	6	4	2	2	2
kg/MT	3	2	1	1	1

[a] References 2 through 6.
[b] Upholstery , belts, hoses, and tires burned in common.
[c] Reference 2.
[d] References 2, 6, and 7 through 9.

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2.5 SEWAGE SLUDGE INCINERATION

By Thomas Lahre

2.5.1 Process Description [1-3]

Incineration is becoming an important means of disposal for the increasing amounts of sludge being produced in sewage treatment plants. Incineration has the advantages of both destroying the organic matter present in sludge, leaving only an odorless, sterile ash, as well as reducing the solid mass by about 90 percent. Disadvantages include the remaining, but reduced, waste disposal problem and the potential for air pollution. Sludge incineration systems usually include a sludge pretreatment stage to thicken and dewater the incoming sludge, an incinerator, and some type of air pollution control equipment (commonly wet scrubbers).

The most prevalent types of incinerators are multiple hearth and fluidized bed units. In multiple hearth units the sludge enters the top of the furnace where it is first dried by contact with the hot, rising, combustion gases, and then burned as it moves slowly down through the lower hearths. At the bottom hearth any residual ash is then removed. In fluidized bed reactors, the combustion takes place in a hot, suspended bed of sand with much of the ash residue being swept out with the flue gas. Temperatures in a multiple hearth furnace are 600°F (320°C) in the lower, ash cooling hearth; 1400 to 2000°F (760 to 1100°C) in the central combustion hearths, and 1000 to 1200°F (540 to 650°C) in the upper, drying hearths. Temperatures in a fluidized bed reactor are fairly uniform, from 1250 to 1500°F (680 to 820°C). In both types of furnace an auxiliary fuel may be required either during startup or when the moisture content of the sludge is too high to support combustion.

2.5.2 Emissions and Controls [1,3,4-7]

Because of the violent upwards movement of combustion gases with respect to the burning sludge, particulates are the major emissions problem in both multiple hearth and fluidized bed incinerators. Wet scrubbers are commonly employed for particulate control and can achieve efficiencies ranging from 95 to 99+ percent.

Although dry sludge may contain from 1 to 2 percent sulfur by weight, sulfur oxides are not emitted in significant amounts when sludge burning is compared with many other combustion processes. Similarly, nitrogen oxides, because temperatures during incineration do not exceed 1500°F (820°C) in fluidized bed reactors or 1600 to 2000°F (870 to 1100°C) in multiple hearth units, are not formed in great amounts.

Odors can be a problem in multiple hearth systems as unburned volatiles are given off in the upper, drying hearths, but are readily removed when afterburners are employed. Odors are not generally a problem in fluidized bed units as temperatures are uniformly high enough to provide complete oxidation of the volatile compounds. Odors can also emanate from the pretreatment stages unless the operations are properly enclosed.

Emission factors for sludge incinerators are shown in Table 2.5-1. It should be noted that most sludge incinerators operating today employ some type of scrubber.

Table 2.5-1. EMISSION FACTORS FOR SEWAGE SLUDGE INCINERATORS EMISSION FACTOR RATING: B

Pollutant	Emissions[a]			
	Uncontrolled[b]		After scrubber	
	lb/ton	kg/MT	lb/ton	kg/MT
Particulate[c]	100	50	3	1.5
Sulfur dioxide[d]	1	0.5	0.8	0.4
Carbon monoxide[e]	Neg	Neg	Neg	Neg
Nitrogen oxides[d] (as NO_2)	6	3	5	2.5
Hydrocarbons[d]	1.5	0.75	1	0.5
Hydrogen chloride gas[d]	1.5	0.75	0.3	0.15

[a] Unit weights in terms of dried sludge.
[b] Estimated from emission factors after scrubbers.
[c] References 6-9.
[d] Reference 8.
[e] References 6, 8.

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3. INTERNAL COMBUSTION ENGINE SOURCES

The internal combustion engine in both mobile and stationary applications is a major source of air pollutant emissions. Internal combustion engines were responsible for approximately 73 percent of the carbon monoxide, 56 percent of the hydrocarbons, and 50 percent of the nitrogen oxides (NO_x as NO_2) emitted during 1970 in the United States.[1] These sources, however, are relatively minor contributors of total particulate and sulfur oxides emissions. In 1970, nationwide, internal combustion sources accounted for only about 2.5 percent of the total particulate and 3.4 percent of the sulfur oxides.[1]

The three major uses for internal combustion engines are: to propel highway vehicles, to propel off-highway vehicles, and to provide power from a stationary position. Associated with each of these uses are engine duty cycles that have a profound effect on the resulting air pollutant emissions from the engine. The following sections describe the many applications of internal combustion engines, the engine duty cycles, and the resulting emissions.

DEFINITIONS USED IN CHAPTER 3

Calendar year – A cycle in the Gregorian calendar of 365 or 366 days divided into 12 months beginning with January and ending with December.

Catalytic device – A piece of emission control equipment that is anticipated to be the major component used in post 1974 light-duty vehicles to meet the Federal emission standards.

Cold vehicle operation – The first 505 seconds of vehicle operation following a 4-hour engine-off period. (for catalyst vehicles a 1-hour engine-off period).

Composite emission factor (highway vehicle) – The emissions of a vehicle in gram/mi (g/km) that results from the product of the calendar year emission rate, the speed correction factor, the temperature correction factor, and the hot/cold weighting correction factor.

Crankcase emissions – Airborne substance emitted to the atmosphere from any portion of the crankcase ventilation or lubrication systems of a motor vehicle engine.

1975 Federal Test Procedure (FTP) – The Federal motor vehicle emission test as described in the *Federal Register*, Vol. 36, Number 128, July 2, 1971.

Fuel evaporative emissions – Vaporized fuel emitted into the atmosphere from the fuel system of a motor vehicle.

Heavy-duty vehicle – A motor vehicle designated primarily for transportation of property and rated at more than 8500 pounds (3856 kilograms) gross vehicle weight (GVW) or designed primarily for transportation of persons and having a capacity of more than 12 persons.

High-altitude emission factors – Substantial changes in emission factors from gasoline-powered vehicles occur as altitude increases. These changes are caused by fuel metering enrichment because of decreasing air density. No relationship between mass emissions and altitude has been developed. Tests have been conducted at near sea level and at approximately 5000 feet (1524 meters) above sea level, however. Because most major U.S. urban areas at high altitude are close to 5000 feet (1524 meters), an arbitrary value of 3500 ft (1067 m) and above is used to define high-altitude cities.

Horsepower-hours – A unit of work.

Hot/cold weighting correction factor – The ratio of pollutant exhaust emissions for a given percentage of cold operation (w) to pollutant exhaust emissions measured on the 1975 Federal Test Procedure (20 percent cold operation) at ambient temperature (t).

Light-duty truck – Any motor vehicle designated primarily for transportation of property and rated at 8500 pounds (3856 kilograms) GVW or less. Although light-duty trucks have a load carrying capability that exceeds that of passenger cars, they are typically used primarily for personal transportation as passenger car substitutes.

Light-duty vehicle (passenger car) – Any motor vehicle designated primarily for transportation of persons and having a capacity of 12 persons or less.

Modal emission model – A mathematical model that can be used to predict the warmed-up exhaust emissions for groups of light-duty vehicles over arbitrary driving sequences.

Model year – A motor vehicle manufacturer's annual production period. If a manufacturer has no annual production period, the term "model year" means a calendar year.

Model year mix – The distribution of vehicles registered by model year expressed as a fraction of the total vehicle population.

Nitrogen oxides – The sum of the nitric oxide and nitrogen dioxide contaminants in a gas sample expressed as if the nitric oxide were in the form of nitrogen dioxide. All nitrogen oxides values in this chapter are corrected for relative humidity.

Speed correction factor – The ratio of the pollutant (p) exhaust emission factor at speed "s" to the pollutant (p) exhaust emission factor as determined by the 1975 Federal Test Procedure at 19.6 miles per hour (31.6 kilometers per hour).

Temperature correction factor – The ratio of pollutant exhaust emissions measured over the 1975 Federal Test Procedure at ambient temperature (t) to pollutant exhaust emissions measured over the 1975 Federal Test Procedure at standard temperature conditions (68 to 86°F).

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3.1 HIGHWAY VEHICLES

Passenger cars, light trucks, heavy trucks, and motorcycles comprise the four main categories of highway vehicles. Within each of these categories, powerplant and fuel variations result in significantly different emission characteristics. For example, heavy trucks may be powered by gasoline or diesel fuel or operate on a gaseous fuel such as compressed natural gas (CNG).

It is important to note that highway vehicle emission factors change with time and, therefore, must be calculated for a specific time period, normally one calendar year. The major reason for this time dependence is the gradual replacement of vehicles without emission control equipment by vehicles with control equipment, as well as the gradual deterioration of vehicles with control equipment as they accumulate age and mileage. The emission factors presented in this chapter cover only calendar years 1971 and 1972 and are based on analyses of actual tests of existing sources and control systems. Projected emission factors for future calendar years are no longer presented in this chapter because projections are "best guesses" and are best presented independently of analytical results. The authors are aware of the necessity for forecasting emissions; therefore, projected emission factors are available in Appendix D of this document.

Highway vehicle emission factors are presented in two forms in this chapter. Section 3.1.1 contains average emission factors for calendar year 1972 for selected values of vehicle miles traveled by vehicle type (passenger cars, light trucks, and heavy trucks), ambient temperature, cold/hot weighting, and average vehicle speed. The section includes one case that represents the average national emission factors as well as thirteen other scenarios that can be used to assess the sensitivity of the composite emission factor to changing input conditions. All emission factors are given in grams of pollutant per kilometer traveled (and in grams of pollutant per mile traveled).

The emission factors given in sections 3.1.2 through 3.1.7 are for individual classes of highway vehicles and their application is encouraged if specific statistical data are available for the area under study. The statistical data required include vehicle registrations by model year and vehicle type, annual vehicle travel in miles or kilometers by vehicle type and age, average ambient temperature, percentage of cold-engine operation by vehicle type, and average vehicle speed. When regional inputs are not available, national values (which are discussed) may be applied.

3.1.1 Average Emission Factors for Highway Vehicles

revised by David S. Kircher
and Marcia E. Williams

3.1.1.1 *General.* Emission factors presented in this section are intended to assist those individuals interested in compiling approximate mobile source emission estimates for large areas, such as an individual air quality region or the entire nation, for calendar year 1972. Projected mobile source emission factors for future years are no longer presented in this section. This change in presentation was made to assure consistency with the remainder of this publication, which contains emission factors based on actual test results on currently controlled sources and pollutants. Projected average emission factors for vehicles are available, however, in Appendix D of this publication.

The emission factor calculation techniques presented in sections 3.1.2 through 3.1.5 of this chapter are strongly recommended for the formulation of localized emission estimates required for air quality modeling or for the evaluation of air pollutant control strategies. Many factors, which vary with geographic location and estimation situation, can affect emission estimates considerably. The factors of concern include average vehicle speed, percentage of cold vehicle operation, percentage of travel by vehicle category (automobiles, light trucks, heavy trucks), and ambient temperature. Clearly, the infinite variations in these factors make it impossible to present composite mobile source emission factors for each application. An effort has been made, therefore, to present average emission factors for a range of conditions. The following conditions are considered for each of these cases:

Average vehicle speed – Two vehicle speeds are considered. The first is an average speed of 19.6 mi/hr (31.6 km/hr), which should be typical of a large percentage of urban vehicle operation. The second is an average speed of 45 mi/hr (72 km/hr), which should be typical of highway or rural operation.

Percentage of cold operation – Three percentages of cold operation are considered. The first (at 31.6 km/hr) assumes that 20 percent of the automobiles and light trucks are operating in a cold condition (representative of vehicle start-up after a long engine-off period) and that 80 percent of the automobiles and light trucks are operating in a hot condition (warmed-up vehicle operation). This condition can be expected to assess the engine temperature situation over a large area for an entire day. The second situation assumes that 100 percent of the automobiles and light trucks are operating in a hot condition (at 72 km/hr). This might be applicable to rural or highway operation. The third situation (at 31.6 km/hr) assumes that 100 percent of the automobiles and light trucks are operating in a cold condition. This might be a worst-case situation around an indirect source such as a sports stadium after an event lets out. In all three situations, heavy-duty vehicles are assumed to be operating in a hot condition.

Percentage of travel by vehicle type – Three situations are considered. The first (at both 31.6 km/hr and 72 km/hr) involves a nationwide mix of vehicle miles traveled by automobiles, light trucks, heavy gasoline trucks, and heavy diesel trucks. The specific numbers are 80.4, 11.8, 4.6, and 3.2 percent of total vehicle miles traveled, respectively.[1, 2] The second (at 31.6 km/hr) examines a mix of vehicle miles traveled that might be found in a central city area. The specific numbers are 63, 32, 2.5, and 2.5 percent, respectively. The third (31.6 km/hr) examines a mix of vehicles that might be found in a suburban location or near a localized indirect source where no heavy truck operation exist. The specific numbers are 88.2, 11.8, 0, and 0 percent, respectively.

Ambient temperature – Two situations at 31.6 km/hr are considered: an average ambient temperature of 24°C (75°F) and an average ambient temperature of 10°C (50°F).

Table 3.1.1-1 presents composite CO, HC, and NO_x factors for the 13 cases discussed above for calendar year 1972. Because particulate emissions and sulfur oxides emissions are not assumed to be functions of the factors discussed above, these emission factors are the same for all scenarios and are also presented in the table. The table entries were calculated using the techniques described and data presented in sections 3.1.2, 3.1.4, and 3.1.5 of this chapter. Examination of Table 3.1.1-1 can indicate the sensitivity of the composite emission factor to various

Table 3.1.1-1. AVERAGE EMISSION FACTORS FOR HIGHWAY VEHICLES, CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Scenario						Emission factors for highway vehicles									
Vehicle weight mix	Average route speed		Ambient temperature		Cold operation	Carbon monoxide		Hydrocarbons		Nitrogen oxides		Particulate		Sulfur oxides	
	mi/hr	km/hr	°F	°C	%	g/mi	g/km	g/mi	g/km	g/mi	g/km	g/mi	g/km	g/mi	g/km
National average	19.6	31.6	75	24	20	76.5	47.5	10.8	6.7	4.9	3.0	0.60	0.37	0.23	0.14
			50	10	20	97.1	60.3	13.0	8.1	5.4	3.4	0.60	0.37	0.23	0.14
			75	24	100	145	90.0	14.6	9.1	4.6	2.9	0.60	0.37	0.23	0.14
			50	10	100	228	142	22.4	13.9	4.6	2.9	0.60	0.37	0.23	0.14
No heavy-duty travel	19.6	31.6	75	24	20	70.6	43.8	9.6	6.0	4.2	2.6	0.54	0.34	0.13	0.08
			50	10	20	92.9	57.7	11.3	7.0	4.7	2.9	0.54	0.34	0.13	0.08
			75	24	100	146	90.7	13.8	8.6	3.8	2.4	0.54	0.34	0.13	0.08
			50	10	100	234	145	22.1	13.7	3.8	2.4	0.54	0.34	0.13	0.08
Central City	19.6	31.6	75	24	20	78.2	48.6	11.2	7.0	4.8	3.0	0.60	0.37	0.20	0.12
			50	10	20	101	62.7	13.7	8.5	5.3	3.3	0.60	0.37	0.20	0.12
			75	24	100	154	95.6	15.6	9.7	4.5	2.8	0.60	0.37	0.20	0.12
			50	10	100	245	152	24.5	15.2	4.5	2.8	0.60	0.37	0.20	0.12
National average	45	72.5	75	24	0	29.8	18.5	4.7	2.9	8.0	5.0	0.60	0.37	0.23	0.14

conditions. A user who has specific data on the input factors should calculate a composite factor to fit the exact scenario. When specific input factor data are not available, however, it is hoped that the range of values presented in the table will cover the majority of applications. The user should be sure, however, that the appropriate scenario is chosen to fit the situation under analysis. In many cases, it is not necessary to apply the various temperature, vehicle speed, and cold/hot operation correction factors because the basic emission factors (24°C, 31.6 km/hr, 20 percent cold operation, nationwide mix of travel by vehicle category) are reasonably accurate predictors of motor vehicle emissions on a regionwide (urban) basis.

References for Section 3.1.1

1. Highway Statistics 1971. U.S. Department of Transportation. Federal Highway Administration. Washington, D.C. 1972. p. 81.

2. 1972 Census of Transportation. Truck Inventory and Use Survey. U.S. Department of Commerce. Bureau of the Census. Washington, D.C. 1974.

3.1.2 Light-Duty, Gasoline-Powered Vehicles (Automobiles)

by David S. Kircher,
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3.1.2.1 General – Because of their widespread use, light-duty vehicles (automobiles) are responsible for a large share of air pollutant emissions in many areas of the United States. Substantial effort has been expended recently to accurately characterize emissions from these vehicles.[1-2] The methods used to determined composite automobile emission factors have been the subject of continuing EPA research, and, as a result, two different techniques for estimating CO, HC, and NO_x exhaust emission factors are discussed in this section.

The first method, based on the Federal Test Procedure (FTP),[3-4] is a modification of the procedure that was discussed in this chapter in earlier editions of AP-42. The second and newer procedure, "modal" emissions analysis, enables the user to input a specific driving pattern (or driving "cycle") and to arrive at an emission rate.[5] The modal technique driving "modes", which include idle, steady-speed cruise, acceleration, and deceleration, are of sufficient complexity that computerization was required. Because of space limitations, the computer program and documentation are not provided in this section but are available elsewhere.[5]

In addition to the methodologies presented for calculating CO, HC, and NO_x exhaust emissions, data are given later in this section for emissions in the idle mode, for crankcase and evaporative hydrocarbon emissions, and for particulate and sulfur oxides emissions.

3.1.2.2 FTP Method for Estimating Carbon Monoxide, Exhaust Hydrocarbons and Nitrogen Oxides Emission Factors – This discussion is begun with a note of caution. At the outset, many former users of this method may be somewhat surprised by the organizational and methodological changes that have occurred. Cause for concern may stem from: (1) the apparent disappearance of "deterioration" factors and (2) the apparent loss of the much-needed capability to project future emission levels. There are, however, substantive reasons for the changes implemented herein.

Results from EPA's annual surveillance programs (Fiscal Years 1971 and 1972) are not yet sufficient to yield a statistically meaningful relationship between emissions and accumulated mileage. Contrary to the previous assumption, emission deterioration can be convincingly related not only to vehicle mileage but also to vehicle age. This relationship may not come as a surprise to many people, but the complications are significant. Attempts to determine a functional relationship between *only* emissions and accumulated mileage have indicated that the data can fit a linear form as well as a non-linear (log) form. Rather than attempting to force the data into a mathematical model, the authors have chosen to present emission factors by both model year and calendar year. The deterioration factors are, therefore, "built in" to the emission factors. This change simplifies the calculations and represents a realistic, sound use of emission surveillance data.

The second change is organizational: emission factors projected to future years are no longer presented in this section. This is in keeping with other sections of the publication, which contains emission factors only for existing sources based on analyses of test results. As mentioned earlier, projections are "best guesses" and are best presented independently of analytical results (see Appendix D).

The calculation of composite exhaust emission factors using the FTP method is given by:

$$e_{npstw} = \sum_{i=n-12}^{n} c_{ipn} m_{in} v_{ips} z_{ipt} r_{iptw} \qquad (3.1.2\text{-}1)$$

where: e_{npstw} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), average speed (s), ambient temperature (t), and percentage cold operation (w)

c_{ipn} = The FTP (1975 Federal Test Procedure) mean emission factor for the i^{th} model year light-duty vehicles during calendar year (n) and for pollutant (p)

m_{in} = The fraction of annual travel by the i^{th} model year light-duty vehicles during calendar year (n)

v_{ips} = The speed correction factor for the i^{th} model year light-duty vehicles for pollutant (p) and average speed (s)

z_{ipt} = The temperature correction factor for the i^{th} model year light-duty vehicles for pollutant (p) and ambient temperature (t)

r_{iptw} = The hot/cold vehicle operation correction factor for the i^{th} model year light-duty vehicles for pollutant (p), ambient temperature (t), and percentage cold operation (w)

The data necessary to complete this calculation for any geographic area are presented in Tables 3.1.2-1 through 3.1.2-8. Each of the variables in Equation 3.1.2-1 is described in greater detail below, after which the technique is illustrated by an example.

Table 3.1.2-1. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT-DUTY VEHICLES —EXCLUDING CALIFORNIA—FOR CALENDAR YEAR 1971[a,b] (BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
Low altitude						
Pre-1968	86.5	53.7	8.74	5.43	3.54	2.20
1968	67.8	42.1	5.54	3.44	4.34	2.70
1969	61.7	38.3	5.19	3.22	5.45	3.38
1970	47.6	29.6	3.77	2.34	5.15	3.20
1971	39.6	24.6	3.07	1.91	5.06	3.14
High altitude						
Pre-1968	126.9	78.8	10.16	6.31	1.87	1.17
1968	109.2	67.8	7.34	4.59	2.20	1.37
1969	76.4	47.4	6.31	3.91	2.59	1.51
1970	94.8	58.9	6.71	4.17	2.78	1.73
1971	88.0	54.6	5.6	3.48	3.05	1.89

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1971. This reflects a substantial change over past presentation of data in this chapter (see text for details).

[b] References 1 and 2. These references summarize and analyze the results of emission tests of light-duty vehicles in several U.S. cities.

Table 3.1.2-2. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT DUTY VEHICLES–STATE OF CALIFORNIA ONLY–FOR CALENDAR YEAR 1971[a,b]

(BASED ON 1975 FEDERAL TEST PROCEDURE)

EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
California						
Pre 1966[c]	86.5	53.7	8.74	5.43	3.54	2.20
1966	65.2	40.5	7.84	4.87	3.40	2.11
1967	67.2	41.7	5.33	3.31	3.42	2.12
1968[c]	67.8	42.1	5.54	3.44	4.34	2.70
1969[c]	61.7	38.3	5.18	3.22	5.45	3.38
1970[c]	50.8	31.5	4.46	2.78	4.62	2.87
1971	42.3	26.3	3.02	1.88	3.83	2.38

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1971. This reflects a substantial change past presentations of data in this chapter (see text for details).

[b] Reference 1. This reference summarizes and analyzes the results of emission tests of light duty vehicles in Los Angeles as well as five other U.S. cities during 1971-1972.

[c] Data for these model years are mean emission test values for the five low altitude test cities summarized in Reference 1.

Table 3.1.2-3. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT DUTY VEHICLES–EXCLUDING CALIFORNIA–FOR CALENDAR YEAR 1972[a,b]

(BASED ON 1975 FEDERAL TEST PROCEDURE)

EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
Low altitude						
Pre 1968	93.5	58.1	8.67	5.38	3.34	2.07
1968	63.7	39.6	6.33	3.93	4.44	2.76
1969	64.2	39.9	4.95	3.07	5.00	3.10
1970	53.2	33.0	4.89	3.04	4.35	2.70
1971	51.1	31.7	3.94	2.45	4.30	2.67
1972	36.9	22.9	3.02	1.88	4.55	2.83
High altitude						
Pre 1968	141.0	87.6	11.9	7.39	2.03	1.26
1968	101.4	63.0	6.89	4.28	2.86	1.78
1969	97.8	60.7	5.97	3.71	2.93	1.82
1970	87.5	54.3	5.56	3.45	3.32	2.06
1971	80.3	49.9	5.19	3.22	2.74	1.70
1972	80.4	50.0	4.75	2.94	3.08	1.91

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1972. This reflects a substantial change over past presentation of data in this chapter (see text for details).

[b] Reference 2. This reference summarizes and analyzes the results of emission tests of light-duty vehicles in six U.S. metropolitan areas during 1972-1973.

Table 3.1.2-4. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT DUTY VEHICLES—STATE OF CALIFORNIA ONLY—FOR CALENDAR YEAR 1972[a,b]
(BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
California						
Pre 1966[c]	93.5	58.1	8.67	5.38	3.34	2.07
1966	86.9	54.0	7.46	4.63	3.43	2.13
1967	75.4	46.8	5.36	3.33	3.77	2.34
1968[c]	63.7	39.6	6.33	3.93	4.44	2.76
1969[c]	64.2	39.9	4.95	3.07	5.00	3.10
1970	78.5	48.7	6.64	4.12	4.46	2.77
1971	59.7	37.1	3.98	2.47	3.83	2.38
1972	46.7	29.0	3.56	2.21	3.81	2.37

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1972. This represents a substantial change over past presentation of data in this chapter (see text for details).

[b] Reference 2. This reference summarizes and analyzes the results of emission tests of light duty vehicles in Los Angeles as well as in five other U.S. cities during 1972-1973.

[c] Data for these model years are mean emission test values for the five low altitude test cities summarized in Reference 2.

Table 3.1.2-5. SAMPLE CALCULATION OF FRACTION OF LIGHT DUTY VEHICLE ANNUAL TRAVEL BY MODEL YEAR[a]

Age, years	1972 Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)[c]	a x b	1972 Fraction of annual travel (m)[d]
1	0.083	15,900	1,320	0.116
2	0.103	15,000	1,545	0.136
3	0.102	14,000	1,428	0.125
4	0.106	13,100	1,389	0.122
5	0.099	12,200	1,208	0.106
6	0.087	11,300	983	0.086
7	0.092	10,300	948	0.083
8	0.088	9,400	827	0.072
9	0.068	8,500	578	0.051
10	0.055	7,600	418	0.037
11	0.039	6,700	261	0.023
12	0.021	6,700	141	0.012
≥13	0.057	6,700	382	0.033

[a] References 6 and 7.

[b] These data are for July 1, 1972, from Reference 7 and represent the U.S. population of light duty vehicles by model year for that year only.

[c] Mileage values are the results of a least squares analysis of data in Reference 6.

[d] $m = ab/\Sigma ab$

Table 3.1.2-6. COEFFICIENTS FOR SPEED CORRECTION FACTORS FOR LIGHT-DUTY VEHICLES[a,b]

Location	Model year	$v_{ips} = e^{(A + BS + CS^2)}$						$v_{ips} = A + BS$	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	0.953	-6.00×10^{-2}	5.81×10^{-4}	0.967	-6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
California	1966-1967	0.957	-5.98×10^{-2}	5.62×10^{-4}	0.981	-6.22×10^{-2}	6.19×10^{-4}	0.844	0.798×10^{-2}
Low altitude	1968	1.070	-6.63×10^{-2}	5.98×10^{-4}	1.047	-6.52×10^{-2}	6.01×10^{-4}	0.888	0.569×10^{-2}
	1969	1.005	-6.27×10^{-2}	5.80×10^{-4}	1.259	-7.72×10^{-2}	6.60×10^{-4}	0.915	0.432×10^{-2}
	1970	0.901	-5.70×10^{-2}	5.59×10^{-4}	1.267	-7.72×10^{-2}	6.40×10^{-4}	0.843	0.798×10^{-2}
	1971-1972	0.943	-5.82×10^{-2}	5.67×10^{-4}	1.241	-7.52×10^{-2}	6.09×10^{-4}	0.843	0.804×10^{-2}
High altitude	1957-1967	0.883	-5.58×10^{-2}	5.52×10^{-4}	0.721	-4.57×10^{-2}	4.56×10^{-4}	0.602	2.027×10^{-2}
	1968	0.722	-4.63×10^{-2}	4.80×10^{-4}	0.662	-4.23×10^{-2}	4.23×10^{-4}	0.642	1.835×10^{-2}
	1969	0.706	-4.55×10^{-2}	4.84×10^{-4}	0.628	-4.04×10^{-2}	4.26×10^{-4}	0.726	1.403×10^{-2}
	1970	0.840	-5.33×10^{-2}	5.33×10^{-4}	0.835	-5.24×10^{-2}	4.38×10^{-4}	0.614	1.978×10^{-2}
	1971-1972	0.787	-4.89×10^{-2}	4.89×10^{-4}	0.894	-5.54×10^{-2}	5.48×10^{-4}	0.697	1.713×10^{-2}

[a] Reference 8. Equations should not be extended beyond the range of the data (15 to 45 mi/hr; 24 to 72 km/hr). For speed correction factors at low speeds (5 and 10 mi/hr; 8 and 16 km/hr) see Table 3.1.2-7.

[b] The speed correction factor equations and coefficients presented in this table are expressed in terms of english units (miles per hour). In order to perform calculations using the metric system of units, it is suggested that kilometers per hour be first converted to miles per hour (1 km/hr = 0.621 mi/hr). Once speed correction factors are determined, all other calculations can be performed using metric units.

Table 3.1.2-7. LOW AVERAGE SPEED CORRECTION FACTORS FOR LIGHT DUTY VEHICLES[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	2.72	1.57	2.50	1.45	1.08	1.03
California	1966-1967	1.70	1.00	1.97	1.12	1.16	1.09
Low altitude	1968	3.06	1.75	2.86	1.66	1.04	1.00
	1969	3.57	1.86	2.95	1.65	1.08	1.05
	1970	3.60	1.88	2.51	1.51	1.13	1.05
	1971-1972	4.15	2.23	2.75	1.63	1.15	1.03
High altitude	1957-1967	2.29	1.48	2.34	1.37	1.33	1.20
	1968	2.43	1.54	2.10	1.27	1.22	1.18
	1969	2.47	1.61	2.04	1.22	1.22	1.08
	1970	2.84	1.72	2.35	1.36	1.19	1.11
	1971-1972	3.00	1.83	2.17	1.35	1.06	1.02

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 9) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr, 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data are approximate and represent the best currently available information.

Table 3.1.2-8. LIGHT DUTY VEHICLE TEMPERATURE CORRECTION FACTORS AND HOT/COLD VEHICLE OPERATION CORRECTION FACTORS FOR FTP EMISSION FACTORS[a]

Pollutant	Temperature correction (z_{ipt})[a]	Hot/Cold operation correction (f(t))[b]
Carbon monoxide	$-0.0127t + 1.95$	$0.0045t + 0.02$
Hydrocarbons	$-0.0113t + 1.81$	$0.0079t + 0.03$
Nitrogen oxides	$-0.0046t + 1.36$	$-0.0068t + 1.64$

[a] Reference 10. Temperature (t) is expressed in °F. In order to apply these equations, °C must be first converted to °F. The appropriate conversion formula is: °F = (9/5)°C + 32. For temperatures expressed on the Kelvin (K) scale: °F = 9/5(K-273.16) + 32.

[b] The formulas for z_{ipt} enable the correction of the FTP emission factors for ambient temperature effects only. The amount of cold/hot operation is not affected. The formulas for f(t), on the other hand, are part of equation 3.1.2-2 for calculating r_{iptw}. The variable r_{iptw} corrects for cold/hot operation as well as ambient temperature.

Note: z_{ipt} can be applied without r_{iptw}, but not vice versa.

FTP emission factor (c_{ipn}). The results of the first two EPA annual light-duty vehicle surveillance programs are summarized in Tables 3.1.2-1 through 3.1.2-4. These data for calendar years 1971 and 1972 are divided by geographic area into: low altitude (excluding California), high altitude (excluding California), and California only. California emission factors are presented separately because, for several model years, California vehicles have been subject to emission standards that differ from standards applicable to vehicles under the Federal emission control program. For those model year vehicles for which California did not have separate emission standards, the national emission factors are assumed to apply in California as well. Emissions at high altitude are differentiated from those at low altitude to account for the effect that altitude has on air-fuel ratios and concomitant emissions. The tabulated values are applicable to calendar years 1971 and 1972 for each model year.

Fraction of annual travel by model year (m_{in}). A sample calculation of this variable is presented in Table 3.1.2-5. In the example, nationwide statistics are used, and the fraction of in-use vehicles by model year (vehicle age) is weighted on the basis of the annual miles driven. The calculation may be "localized" to reflect local (county, state, etc.) vehicle age mix, annual miles driven, or both. Otherwise, the national data can be used. The data presented in Table 3.1.2-5 are for calendar year 1972 only; for later calendar years, see Appendix D.

Speed Correction Factors (v_{ips}). Speed correction factors enable the "adjustment" of FTP emission factors to account for differences in average route speed. Because the implicit average route speed of the FTP is 19.6 mi/hr (31.6 km/hr), estimates of emissions at higher or lower average speeds require a correction.

It is important to note the difference between "average route speed" and "steady speed". Average route speed is trip-related and based on a composite of the driving modes (idle, cruise, acceleration, deceleration) encountered, for example, during a typical home-to-work trip. Steady speed is highway facility-oriented. For instance, a group of vehicles traveling over an uncongested freeway link (with a volume to capacity ratio of 0.1, for example) might be traveling at a steady speed of about 55 mi/hr (89 km/hr). Note, however, that steady speeds, even at the link level, are unlikely to occur where resistance to traffic flow occurs (unsynchronized traffic signaling, congested flow, etc.).

In previous revisions to this section, the limited data available for correcting for average speed were presented graphically. Recent research, however, has resulted in revised speed relationships by model year.[9] To facilitate the presentation, the data are given as equations and appropriate coefficients in Table 3.1.2-6. These relationships were developed by performing five major tasks. First, urban driving pattern data collected during the CAPE-10 Vehicle Operations Survey[11] were processed by city and time of day into freeway, non-freeway, and composite speed-mode matrices. Second, a large number of driving patterns were computer-generated for a range of average speeds (15 to 45 mi/hr; 24 to 72 km/hr) using weighted combinations of freeway and non-freeway matrices. Each of these patterns was filtered for "representativeness." Third, the 88 resulting patterns were input (second-by-second speeds) to the EPA modal emission analysis model (see sections 3.1.2.3). The output of the model was estimated emissions for each pattern of 11 vehicle groups (see Table 3.1.2-6 for a listing of these groups). Fourth, a regression analysis was performed to relate estimated emissions to average route speed for each of the 11 vehicle groups. Fifth, these relationships were normalized to 19.6 mi/hr (31.6 km/hr) and summarized in Table 3.1.2-6.

The equations in Table 3.1.2-6 apply only for the range of the data – from 15 to 45 mi/hr (24 to 72 km/hr). Because there is a need, in some situations, to estimate emissions at very low average speeds, correction factors for 5 and 10 mi/hr (8 and 16 km/hr) presented in Table 3.1.2-7 were developed using a method somewhat like that described above, again using the modal emission model. The modal emission model predicts emissions from warmed-up vehicles. The use of this model to develop speed correction factors makes the assumption that a given speed correction factor applies equally well to hot and cold vehicle operation. Estimation of warmed-up idle emissions are presented in section 3.1.2.4 on a gram per minute basis.

Temperature Correction Factor (z_{ipt}). The 1975 FTP requires that emissions measurements be made within the limits of a relatively narrow temperature band (68 to 86°F). Such a band facilitates uniform testing in laboratories without requiring extreme ranges of temperature control. Present emission factors for motor vehicles are based on data from the standard Federal test (assumed to be at 75°F). Recently, EPA and the Bureau of Mines undertook a test program to evaluate the effect of ambient temperature on motor vehicle exhaust emission levels.[10] The study indicates that changes in ambient temperature result in significant changes in emissions during cold start-up operation. Because many Air Quality Control Regions have temperature characteristics differing considerably from the 68 to 86°F range, the temperature correction factor should be applied. These correction factors, which can be applied between 20 and 80°F, are presented in Table 3.1.2-8. For temperatures outside this range, the appropriate endpoint correction factor should be applied.

Hot/Cold Vehicle Operation Correction Factor (z_{iptw}). The 1975 FTP measures emissions during: a cold transient phase (representative of vehicle start-up after a long engine-off period), a hot transient phase (representative of vehicle start-up after a short engine-off period), and a stabilized phase (representative of warmed-up vehicle operation). The weighting factors used in the 1975 FTP are 20 percent, 27 percent, and 53 percent of total miles (time) in each of the three phases, respectively. Thus, when the 1975 FTP emission factors are applied to a given region for the purpose of assessing air quality, 20 percent of the light-duty vehicles in the area of interest are assumed to be operating in a cold condition, 27 percent in a hot start-up condition, and 53 percent in a hot stabilized condition. For non-catalyst equipped vehicles (all pre-1975 model year vehicles), emissions in the two hot phases are essentially equivalent on a grams per mile (grams per kilometer basis). Therefore, the 1975 FTP emission factor represents 20 percent cold operation and 80 percent hot operation.

Many situations exist in which the application of these particular weighting factors may be inappropriate. For example, light-duty vehicle operation in the center city may have a much higher percentage of cold operation during the afternoon peak when work-to-home trips are at a maximum and vehicles have been standing for 8 hours. The hot/cold vehicle operation correction factor allows the cold operation phase to range from 0 to 100 percent of total light-duty vehicle operations. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$z_{iptw} = \frac{w + (100-w)\,f(t)}{20 + 80\,f(t)} \qquad (3.1.2\text{-}3)$$

where: f(t) is given in Table 3.1.2-8.

Sample Calculation. As a means of further describing the application of equation 3.1.2-1, calculation of the carbon monoxide composite emission factor is provided as an example. To perform this calculation (or any calculation using this procedure), the following questions must be answered:

1. What calendar year is being considered?

2. What is the average vehicle speed in the area of concern?

3. Is the area at low altitude (non-California), in California, or at high altitude?

4. Are localized vehicle mix and/or annual travel data available?

5. Which pollutant is to be estimated? (For non-exhaust hydrocarbons see section 3.1.2.5).

6. What is the ambient temperature (if it does not fall within the 68 to 86°F Federal Test Procedure range)?

7. What percentage of vehicle operation is cold operation (first 500 seconds of operation after an engine-off period of at least 4 hours)?

For this example, the composite carbon monoxide emission factor for 1972 will be estimated for a hypothetical county. Average vehicle speed for the county is assumed to be 30 mi/hr. The county is at low altitude (non-California), and localized vehicle mix/annual travel data are unavailable (nationwide statistics are to be used). The ambient temperature is assumed to be 50°F and the percentage of cold vehicle operation is assumed to be 40 percent. To simplify the presentation, the appropriate variables are entered in the following tabulation.

Model year(s)	Variables,ᵃ c_{ipn}	m_{in}	v_{ips}	z_{ipt}	r_{iptw}	$(c_{ipn})(m_{in})(v_{ips})$ $(z_{ipt})(r_{iptw})$
Pre-1968	58.1	0.396	0.72	1.315	1.39	30.3
1968	39.6	0.106	0.69	1.315	1.39	5.3
1969	39.9	0.122	0.63	1.315	1.39	5.6
1970	33.0	0.126	0.62	1.315	1.39	4.7
1971	31.7	0.135	0.63	1.315	1.39	4.9
1972	22.9	0.118	0.63	1.315	1.39	3.1

e_{npstw} = 53.9 g/km

[a] The variable c_{ipn} above is from Table 3.1.2-3, and the variable m_{in} was taken from the sample calculation based on nationwide data, Table 3.1.2-5. The fraction of travel for pre-1968 (8 years old and older) vehicles is the sum of the last eight values in the far right-hand column of the table. The speed correction factor (v_{ips}) was calculated from the appropriate equations in Table 3.1.2-6. The variable z_{ipt} was calculated from the appropriate equation in Table 3.1.2-8. The variable r_{iptw} was calculated using an equation from Table 3.1.2-8 and equation 3.1.2-2.

The resultant composite carbon monoxide emission factor for 1972 for the hypothetical county is 53.9 g/km.

3.1.2.3 Modal Emission Model for Estimating Carbon Monoxide, Hydrocarbons, and Nitrogen Oxides Emission Factors – The modal emission model and allied computer programs permit an analyst to calculate mass emission quantities of carbon monoxide, hydrocarbons, and nitrogen oxides emitted by individual vehicles or groups of vehicles over any specified driving sequence or pattern. The complexity of the model and accompanying computer programs makes presentation of the entire procedure in this publication impractical. Instead, the capabilities and limitations of the model are briefly described in the following paragraphs with the details to be found in a separate report, *Automobile Exhaust Emission Modal Analysis Model*.[3]

The modal emission model was developed because of the well-established fact that emission rates for a particular vehicle depend upon the manner in which it is operated. Stated another way, the emissions from a particular vehicle are a function of the time it spends in each of four general operating modes (idle, cruise, deceleration, acceleration) as well as specific operation within each of the four modes. In many situations, use of the basic FTP emission factors may be sufficient. Certainly, nationwide, statewide, and county-wide emission estimates that involve spatial aggregation of vehicular travel data lend themselves to the FTP method (section 3.1.2.2). There are, however, a relatively large number of circumstances for which an analyst may require emission estimates at a zonal or link level of aggregation. The analyst, for example, may be faced with providing inputs to a carbon monoxide dispersion model, estimating the impact of an indirect source (sports complex, shopping center, etc.), or preparing a highway impact statement. In such instances, the resources may be available to determine the necessary inputs to the modal model either by estimation or field studies. These data are input to the modal model and emission estimates are output.

Although the computer software package is sufficiently flexible to accept any set of input modal emission data, EPA data based on tests of 1020 individual light-duty vehicles (automobiles) that represent variations in model year, manufacture, engine and drive train equipment, accumulated mileage, state of maintenance, attached pollution abatement devices, and geographic location are a part of the package. The user, therefore, need not input any modal emission data. He inputs the driving sequence desired as speed (mi/hr) versus time (sec) in 1-second intervals and specifies the vehicle mix for which emission estimates are desired (vehicles are grouped by model year and geographic location). The output of the model can then be combined with the appropriate traffic volume for the desired time period to yield an emission estimate. The use of the modal emission model to estimate a composite emission factor does not, however, eliminate the need for temperature and cold/hot weighting correction factors. The model predicts emissions from warmed-up vehicles at an ambient temperature of approximately 75°F. The estimate of composite exhaust emission factors using the modal emission model is given by:

$$e_{ptw} = c_p \, g_{pt} \, h_{ptw} \qquad (3.1.2\text{-}3)$$

where: e_{ptw} = Composite emission factor in grams per mile (g/km) for calendar year 1971, pollutant (p), ambient temperature (t), percentage cold operation (w), and the specific driving sequence and vehicle mix specified

c_p = The mean emission factor for pollutant (p) for the specified vehicle mix and driving sequence

a_{pt} = The temperature correction factor for pollutant (p) and temperature (t) for warmed-up operation

b_{ptw} = The hot/cold vehicle operation correction factor for pollutant (p), temperature (t), and percentage cold operation (w)

The data necessary to compute a_{pt} and b_{ptw} are given in Table 3.1.2-9. The modal analysis computer program is necessary to compute c_p.[3]

Table 3.1.2-9. LIGHT DUTY VEHICLE MODAL EMISSION MODEL CORRECTION FACTORS FOR TEMPERATURE AND COLD/HOT START WEIGHTING[a]

Pollutant	Temperature correction (a_{pt})	Hot/cold temperature correction (R(t))
Carbon monoxide	1.0	0.0045 t + 0.02
Hydrocarbons	1.0	0.0079 t + 0.03
Nitrogen oxides	-0.0065 t + 1.49	-0.0068 t + 1.64

[a] Reference 10. Temperature is expressed in °F. In order to apply these equations, convert °C to °F (F = 9/5C + 32) or °K to °F (F = 9/5(K-273.16) + 32).

Temperature Correction Factor (a_{pt}). The modal analysis model predicts emissions at approximately 75°F. The temperature correction factors are expressed in equational form and presented in Table 3.1.2-9.

Hot/Cold Vehicle Operation Correction Factor (b_{ptw}). The modal analysis model predicts emissions during warmed-up vehicle operation, but there are many urban situations for which this assumption is not appropriate. The hot/cold vehicle operation correction factor allows for the inclusion of a specific percentage of cold operation. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$b_{ptw} = \frac{w + (100 - w)R(t)}{100\,R(t)} \qquad (3.1.2\text{-}4)$$

where: R(t) is given in Table 3.1.2-9.

It is important that potential users of modal analysis recognize of the important limitations of the model. Although the model provides the capability of predicting emission estimates for any driving pattern, it can only predict emissions for the vehicle groups that have been tested. Presently this capability is limited to 1971 and older light-duty vehicles. Efforts are underway to add additional model years (1972-1974), and new models will be tested as they become available. Although the model is not directly amenable to projecting future year emissions, it can predict "base" year emissions. Future year emissions can be estimated using the ratio of future year to base year emissions based on FTP composite emission factors. Finally, the technique requires the input of a driving sequence and the use of a computer, and is therefore, more complex and more costly to use than the simple FTP technique (section 3.1.2.1).

The modal procedure discussion in this section is recommended when the user is interested in comparing emissions over several different specific driving scenarios. Such an application will result in more accurate comparisons than can be obtained by the method given in section 3.1.2.2. For other applications where average speed is all that is known or when calendar year to calendar year comparisons are required, the method in section 3.1.2.2 is recommended.

3.1.2.4 Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Idle Emission Factors – Estimates of emissions during a vehicles' idle operating mode may be appropriate at trip attractions such as shopping centers, airports, sports complexes, etc. Because idle emission factors are expressed (by necessity) in terms of elapsed time, emissions at idle can be estimated using vehicle operating minutes rather than the conventional vehicle miles of travel.

Application of the idle values (Table 3.1.2-10) requires calculation of a composite idle emission factor (c_{ip}) through the use of the variable m_{in} (see section 3.1.2.2) and i_{ip} (idle pollutant p emission factor for the i^{th} model year). The temperature and hot/cold weighting factors presented in Table 3.1.2-9 apply to idle emissions. The tabulated values are based on warmed-up emissions. (For a_{pt}, see Table 3.1.2-9; for b_{ptw}, see Table 3.1.2-9 and equation 3.1.2-4.)

Table 3.1.2-10. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EMISSION FACTORS FOR LIGHT-DUTY VEHICLES IN WARMED-UP IDLE MODE[a]
(grams/minute)

Location and model year(s)	Carbon monoxide	Exhaust hydrocarbons	Nitrogen oxides
Low altitude			
Pre-1968	16.9	1.63	0.06
1968	15.8	1.32	0.12
1969	17.1	1.17	0.12
1970	13.1	0.73	0.13
1971	13.0	0.83	0.11
High altitude			
Pre-1968	18.6	1.83	0.11
1968	16.8	1.09	0.11
1969	16.6	0.90	0.10
1970	16.6	1.13	0.11
1971	16.9	0.80	0.16
California only (low altitude)			
Pre-1966	16.9	1.63	0.08
1966	18.7	1.27	0.07
1967	18.7	1.27	0.07
1968	15.8	1.32	0.12
1969	17.1	1.17	0.12
1970	10.3	0.76	0.28
1971	13.3	0.78	0.18

[a] Reference 13.

The mathematical expression is simply:

$$i_p = \sum_{i=n-12}^{n} i_{ip}\, m_{in}\, z_{ipt}\, r_{iptw} \qquad (3.1.2\text{-}5)$$

Because the idle data are from the same data base used to develop the modal analysis procedure, they are subject to the same limitations. Most importantly, idle values cannot be directly used to estimate future emissions.

3.1.2.5 Crankcase and Evaporative Hydrocarbon Emission Factors – In addition to exhaust emission factors, the calculation of hydrocarbon emission from gasoline motor vehicles involves evaporative and crankcase hydrocarbon emission factors. Composite crankcase emissions can be determined using:

$$f_n = \sum_{i=n-12}^{n} h_i\, m_{in} \qquad (3.1.2\text{-}6)$$

where: f_n = The composite crankcase hydrocarbon emission factor for calendar year (n)

h_i = The crankcase emission factor for the i^{th} model year

m_{in} = The weighted annual travel of the i^{th} year during calendar year (n)

Crankcase hydrocarbon emission factor by model year are summarized in Table 3.1.2-11.

The two major sources of evaporative hydrocarbon emissions from light duty vehicles are the fuel tank and the carburetor system. Diurnal changes in ambient temperature result in expansion of the air-fuel mixture in a partially filled fuel tank. As a result, gasoline vapor is expelled to the atmosphere. Running losses from the fuel tank occur as the fuel is heated by the road surface during driving, and hot soak losses from the carburetor system occur after engine shut down at the end of a trip. These carburetor losses are from locations such as: the

Table 3.1.2-11. CRANKCASE HYDROCARBON EMISSIONS BY MODEL YEAR FOR LIGHT DUTY VEHICLES EMISSION FACTOR RATING: B

Model year	Hydrocarbons	
	g/mi	g/km
California only		
Pre 1961	4.1	2.5
1961 through 1963	0.8	0.5
1964 through 1967	0.0	0.0
Post 1967	0.0	0.0
All areas except California		
Pre 1963	4.1	2.5
1963 through 1967	0.8	0.5
Post 1967	0.0	0.0

[a] Reference 13.

carburetor vents, the float bowl, and the gaps around the throttle and choke shafts. Because evaporative emissions are a function of the diurnal variation in ambient temperature and the number of trips per day, emissions are best calculated in terms of evaporative emissions per day per vehicle. Emissions per day can be converted to emissions per mile (if necessary) by dividing by an average daily miles per vehicle value. This value is likely to vary from location to location, however. The composite evaporative hydrocarbon emission factor is given by:

$$e_n = \sum_{i=n-12}^{n} (g_i + k_i d)(m_i) \qquad (3.1.2\text{-}7)$$

where: e_n = The composite evaporative hydrocarbon emission factor for calendar year (n) in lb/day (g/day)

g_i = The diurnal evaporative hydrocarbon emission factor for model year (i) in lb/day (g/day)

k_i = The hot soak evaporative emission factor in lb/trip (g/trip) for the i^{th} model year

d = The number of daily trips per vehicle (3.3 trips/vehicle-day is the nationwide average)

m_i = The fraction of annual travel by the i^{th} model year during calendar year n

The variables g_i and k_i are presented in Table 3.1.2-12 by model year.

Table 3.1.2-12. EVAPORATIVE HYDROCARBON EMISSION FACTORS BY MODEL YEAR FOR LIGHT-DUTY VEHICLES[a]
EMISSION FACTOR RATING: A

Location and model year	By source[b]		Composite emissions[c]		
	Diurnal, g/day	Hot soak, g/trip	g/day	g/mi	g/km
Low altitude					
Pre-1970	26.0	14.7	74.5	2.53	1.57
1970 (Calif.)	16.3	10.9	52.3	1.78	1.11
1970 (non-Calif.)	26.0	14.7	74.5	2.53	1.57
1971	16.3	10.9	52.3	1.78	1.11
1972	12.1	12.0	51.7	1.76	1.09
High altitude[d]					
Pre-1971	37.4	17.4	94.8	3.22	2.00
1971-1972	17.4	14.2	64.3	2.19	1.36

[a] References 1, 14 and 15.

[b] See text for explanation.

[c] Gram per day values are diurnal emissions plus hot soak emissions multiplied by the average number of trips per day. Nationwide data from References 16 and 17 indicate that the average vehicle is used for 3.3 trips per day. Gram per mile values were determined by dividing average g/day by the average nationwide travel per vehicle (29.4 mi/day) from Reference 18.

[d] Vehicles without evaporative control were not tested at high altitude. Values presented here are the product of the ratio of pre-1971 (low altitude) evaporative emissions to 1972 evaporative emissions and 1971-1972 high altitude emissions.

3.1.2.6 Particulate and Sulfur Oxide Emissions – Light-duty, gasoline-powered vehicles emit relatively small quantities of particulate and sulfur oxides in comparison with the emissions of the three pollutants discussed above. For this reason, average rather than composite emission factors should be sufficiently accurate for approximating particulate and sulfur oxide emissions from light-duty, gasoline-powered vehicles. Average emission factors for these pollutants are presented in Table 3.1.2-13. No Federal standards for these two pollutants are presently in effect, although many areas do have opacity (antismoke) regulations applicable to motor vehicles.

Table 3.1.2-13. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR LIGHT DUTY VEHICLES
EMISSION FACTOR RATING: C

Pollutant	Emissions for Pre-1973 vehicles	
	g/mi	g/km
Particulate[a]		
Exhaust	0.34	0.21
Tire wear	0.20	0.12
Sulfur oxides[b] (SO_x as SO_2)	0.13	0.08

[a] References 18, 19, and 20.

[b] Based on an average fuel consumption of 13.6 mi/gal (5.8 km/liter) from Reference 21 and on the use of a fuel with a 0.032 percent sulfur content from References 22 through 24 and a density of 6.1 lb/gal (0.73 kg/liter) from References 22 and 23.

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3.1.3 Light-Duty, Diesel-Powered Vehicles

by David S. Kircher

3.1.3.1 General – In comparison with the conventional, "uncontrolled," gasoline-powered, spark-ignited, automotive engine, the uncontrolled diesel automotive engine is a low pollution powerplant. In its uncontrolled form, the diesel engine emits (in grams per mile) considerably less carbon monoxide and hydrocarbons and somewhat less nitrogen oxides than a comparable uncontrolled gasoline engine. A relatively small number of light-duty diesels are in use in the United States.

3.1.3.2 Emissions – Carbon monoxide, hydrocarbons, and nitrogen oxides emission factors for the light-duty, diesel-powered vehicle are shown in Table 3.1.3-1. These factors are based on tests of several Mercedes 220D automobiles using a slightly modified version of the Federal light-duty vehicle test procedure.[1-2] Available automotive diesel test data are limited to these results. No data are available on emissions versus average speed. Emissions from light-duty diesel vehicles during a calendar year (n) and for a pollutant (p) can be approximately calculated using:

$$e_{np} = \sum_{i=n-12}^{n} c_{ipn} m_{in} \qquad (3.1.2\text{-}1)$$

where: e_{np} = Composite emission factor in grams per vehicle mile for calendar year (n) and pollutant (p)

c_{ipn} = The 1975 Federal test procedure emission rate for pollutant (p) in grams/mile for the i^{th} model year at calendar year (n) (Table 3.1.3-1)

m_{in} = The fraction of total light-duty diesel vehicle miles driven by the i^{th} model year diesel light-duty vehicles

Details of this calculation technique are discussed in section 3.1.2.

The emission factors in Table 3.1.3-1 for particulates and sulfur oxides were developed using an average sulfur content fuel in the case of sulfur oxides and the Dow Measuring Procedure on the 1975 Federal test cycle for particulate.[1-6]

Table 3.1.3-1. EMISSION FACTORS FOR LIGHT-DUTY, DIESEL-POWERED VEHICLES
EMISSION FACTOR RATING: B

	Emission factors, Pre-1973 model years	
Pollutant	g/mi	g/km
Carbon monoxide[a]	1.7	1.1
Exhaust hydrocarbons	0.46	0.29
Nitrogen oxides[a,b] (NO_x as NO_2)	1.6	0.99
Particulate[b]	0.73	0.46
Sulfur oxides[c]	0.54	0.34

[a] Estimates are arithmetic mean of tests of vehicles. References 3 through 5 and 7.

[b] Reference 4.

[c] Calculated using the fuel consumption rate reported in Reference 7 and assuming the use of a diesel fuel containing 0.20 percent sulfur.

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3.1.4 Light-Duty, Gasoline-Powered Trucks and Heavy-Duty, Gasoline-Powered Vehicles

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3.1.4.1 General — This vehicle category consists of trucks and buses powered by gasoline-fueled, spark-ignited internal combustion engines that are used both for commercial purposes (heavy trucks and buses) and personal transportation (light trucks). In addition to the use classification, the categories cover different gross vehicle weight (GVW) ranges. Light trucks range from 0 to 8500 pounds GVW (0 to 3856 kg GVW); heavy-duty vehicles have GVWs of 8501 pounds (3856 kg) and over. The light-duty truck, because of its unique characteristics and usage, is treated in a separate category in this revision to AP-42. Previously, light trucks with a GVW of 6000 pounds (2722 kg) or less were included in section 3.1.2 (Light-Duty, Gasoline-Powered Vehicles), and light trucks with a GVW of between 6001 and 8500 pounds (2722-3855 kg) were included in section 3.1.4 (Heavy-Duty, Gasoline-Powered Vehicles).

3.1.4.2 Light-Duty Truck Emissions — Because of many similarities to the automobile, light truck emission factor calculations are very similar to those presented in section 3.1.2. The most significant difference is in the Federal Test Procedure emission rate.

3.1.4.2.1 Carbon monoxide, hydrocarbon, and nitrogen oxides emissions — The calculation of composite exhaust emission factors using the FTP method is given by:

$$e_{npstw} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \, v_{ips} \, z_{ipt} \, r_{iptw} \qquad (3.1.4\text{-}1)$$

where: e_{npstw} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), average speed (s), ambient temperature (t), and percentage cold operation (w)

c_{ipn} = The FTP (1975 Federal Test Procedure) mean emission factor for the i_{th} model year light-duty trucks during calendar year (n) and for pollutant (p)

m_{in} = The fraction of annual travel by the i^{th} model year light-duty trucks during calendar year (n)

v_{ips} = The speed correction factor for the i^{th} model year light-duty trucks for pollutant (p) and average speed (s)

z_{ipt} = The temperature correction for the i^{th} model year light-duty trucks for pollutant (p) and ambient temperature (t)

r_{iptw} = The hot/cold vehicle operation correction factor for the i_{th} model year light-duty trucks for pollutant (p), ambient temperature (t), and percentage of cold operation (w)

The data necessary to complete this calculation for any geographic area are presented in Tables 3.1.4-1 through 3.1.4-3. Each of the variables in equation 3.1.4-1 is described in greater detail below. The technique is illustrated by example in section 3.1.3.

Table 3.1.4-1. EXHAUST EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS FOR CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Location	Model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides	
		g/mi	g/km	g/mi	g/km	g/mi	g/km
All areas except high altitude and California[a]	Pre-1968[a]	125	77.6	17.0	10.6	4.2	2.6
	1968	66.5	41.3	7.1	4.4	4.9	3.0
	1969	64.3	39.9	5.3	3.3	5.3	3.3
	1970	53.5	33.2	4.8	3.0	5.2	3.2
	1971	53.5	33.2	4.2	2.6	5.2	3.2
	1972	42.8	26.6	3.4	2.1	5.3	3.3
High altitude[b]	Pre-1968	189	117	23.3	14.5	2.6	1.6
	1968	106	65.8	9.7	6.0	3.2	2.0
	1969	98.0	60.9	6.4	4.0	3.1	1.9
	1970	88.0	54.6	5.5	3.4	4.0	2.5
	1971	84.1	52.2	5.5	3.4	3.3	2.0
	1972	84.1	52.2	5.3	3.3	3.6	2.2

[a] References 1 through 4. California emission factors can be estimated as follows:

1. Use pre-1968 factors for all pre-1966 California light trucks.
2. Use 1968 factors for all 1966-1968 California light trucks.
3. For 1969-1972, use the above values multiplied by the ratio of California LDV emission factors to low altitude LDV emission factors (see section 3.1.2).

[b] Based on light-duty emission factors at high altitude compared with light-duty emission factors at low altitude (section 3.1.2).

Table 3.1.4-2. COEFFICIENTS FOR SPEED ADJUSTMENT CURVES FOR LIGHT-DUTY TRUCKS[a]

Location	Model year	Exp. (A + BS + CS²)						Exp. (A + BS)	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude (excluding 1966-1967 Calif.)	1957-1967	0.953	6.19×10^{-2}	5.81×10^{-4}	0.967	6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
California	1966-1967	0.957	5.98×10^{-2}	5.63×10^{-4}	0.981	6.22×10^{-2}	6.19×10^{-4}	0.844	0.198×10^{-2}
Low altitude	1968	1.070	6.63×10^{-2}	6.98×10^{-4}	1.047	6.62×10^{-2}	6.01×10^{-4}	0.888	0.569×10^{-2}
	1969	1.005	6.27×10^{-2}	6.80×10^{-4}	1.259	7.72×10^{-2}	6.60×10^{-4}	0.915	0.432×10^{-2}
	1970	0.901	5.70×10^{-2}	5.59×10^{-4}	1.207	7.72×10^{-2}	6.40×10^{-4}	0.843	0.750×10^{-2}
	1971-1972	0.943	6.97×10^{-2}	6.67×10^{-4}	1.241	7.57×10^{-2}	6.09×10^{-4}	0.843	0.802×10^{-2}
High altitude	1957-1967	0.883	5.58×10^{-2}	6.52×10^{-4}	0.721	4.67×10^{-2}	4.56×10^{-4}	0.802	2.027×10^{-2}
	1968	0.722	4.63×10^{-2}	4.80×10^{-4}	0.667	4.23×10^{-2}	4.33×10^{-4}	0.642	1.636×10^{-2}
	1969	0.706	4.55×10^{-2}	4.84×10^{-4}	0.628	4.04×10^{-2}	4.26×10^{-4}	0.726	1.403×10^{-2}
	1970	0.840	5.33×10^{-2}	5.33×10^{-4}	0.836	5.21×10^{-2}	4.98×10^{-4}	0.614	1.978×10^{-2}
	1971-1972	0.787	4.99×10^{-2}	4.99×10^{-4}	0.894	5.54×10^{-2}	4.89×10^{-4}	0.697	1.713×10^{-2}

[a] Reference 5. Equations should not be extrapolated beyond the range of data (15 to 45 mi/hr). These data are for light-duty vehicles and are assumed applicable to light-duty trucks.

Table 3.1.4-3. LOW AVERAGE SPEED CORRECTION FACTORS FOR LIGHT-DUTY TRUCKS[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	2.72	1.57	2.50	1.45	1.08	1.03
California	1966-1967	1.79	1.00	1.87	1.12	1.16	1.09
Low altitude	1968	3.06	1.75	2.96	1.66	1.04	1.00
	1969	3.57	1.86	2.95	1.65	1.08	1.05
	1970	3.60	1.88	2.51	1.51	1.13	1.05
	1971-1972	4.15	2.23	2.75	1.63	1.15	1.03
High altitude	1957-1967	2.29	1.48	2.34	1.37	1.33	1.20
	1968	2.43	1.54	2.10	1.27	1.22	1.18
	1969	2.47	1.61	2.04	1.22	1.22	1.08
	1970	2.84	1.72	2.35	1.36	1.19	1.11
	1971-1972	3.00	1.83	2.17	1.35	1.06	1.02

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 6) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr; 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data are approximate and represent the best currently available information.

Table 3.1.4-4. SAMPLE CALCULATION OF FRACTION OF ANNUAL LIGHT-DUTY TRUCK TRAVEL BY MODEL YEAR[a]

Age, years	Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)	a x b	Fraction of annual travel (m)[c]
1	0.061	15,900	970	0.094
2	0.095	15,000	1,425	0.138
3	0.094	14,000	1,316	0.127
4	0.103	13,100	1,349	0.131
5	0.083	12,200	1,013	0.098
6	0.076	11,300	859	0.083
7	0.076	10,300	783	0.076
8	0.063	9,400	592	0.057
9	0.054	8,500	459	0.044
10	0.043	7,600	327	0.032
11	0.036	6,700	241	0.023
12	0.024	6,700	161	0.016
≥13	0.185	4,500	832	0.081

[a] Vehicles in use by model year as of 1972 (Reference 7).
[b] References 7 and 8.
[c] m = ab/Σab.

Table 3.1.4-5. LIGHT DUTY TRUCK TEMPERATURE CORRECTION FACTORS AND HOT/COLD VEHICLE OPERATION CORRECTION FACTORS FOR FTP EMISSION FACTORS[a]

Pollutant	Temperature correction (z_{ipt})[b]	Hot/cold operation correction (f(t))[b]
Carbon monoxide	-0.0127 t + 1.95	0.0045 t + 0.02
Hydrocarbons	-0.0113 t + 1.81	0.0079 t + 0.03
Nitrogen oxides	-0.0046 t + 1.36	-0.0068 t + 1.64

[a] Reference 9. Temperature (t) is expressed in °F. In order to apply these equations, °C must be first converted to °F. The appropriate conversion formula is: °F = (9/5)°C + 32. For temperatures expressed on the Kelvin (K) scale: °F = 9/5 (K-273.16) + 32.

[b] The formulae for z_{ipt} enable the correction of the FTP emission factors for ambient temperature effects only. The amount of cold/hot operation is not affected. The formulae for f(t), on the other hand, are part of equation 3.1.4-2 for calculating r_{iptw}. The variable r_{iptw} corrects for cold/hot operation as well as ambient temperature. Note: z_{ipt} can be applied without r_{iptw}, but not vice versa.

FTP Emission Factor (c_{ipn}). The results of the EPA light-duty truck surveillance programs are summarized in Table 3.1.4-1. These data are divided by geographic area into: low altitude (non-California), high altitude, and California only. California emission factors are presented separately (as a footnote) because light-duty trucks operated in California have been, in the case of several model years, subject to emission standards that differ from those standards applicable to light trucks under the Federal emission control program. Emissions at high altitude are differentiated from those at low altitude to account for the effect that altitude has on air/fuel ratios and concomitant emissions. The tabulated values are applicable to calendar year 1972 for each model year.

Fraction of Annual Travel by Model Year (m_{in}). A sample calculation of this variable is presented in Table 3.1.4-4. In the example, nationwide statistics are used and the fraction of in-use vehicles by model year (vehicle age) are weighted on the basis of the annual miles driven (again, nationwide data are used). The calculation may be "localized" to reflect local (county, state, etc.) vehicle age mix, annual miles driven, or both. Otherwise, the national data can be used. The data presented in Table 3.1.4-4 are for calendar year 1972 only. For later calendar years, see Appendix D.

Speed Correction Factors (v_{ips}). Speed correction factors enable the "adjustment" of FTP emission factors to account for differences in average route speed. Because the implicit average route speed of the FTP is 19.6 mi/hr (31.6 km/hr), estimates of emissions at higher or lower average speeds require a correction.

It is important to note the difference between "average route speed" and "steady speed." Average route speed is trip related and based on a composite of the driving modes (idle, cruise, acceleration, deceleration) encountered during a typical home-to-work trip, for example. Steady speed is highway facility oriented. For instance, a group of vehicles traveling over an uncongested freeway link (with a volume to capacity ratio of 0.1, for example) might be traveling at a steady speed of about 55 mi/hr (89 km/hr). Note, however, that steady speeds, even at the link level, are unlikely to occur where resistance to traffic flow occurs (unsynchronized traffic signaling, congested flow, etc.).

In previous revisions to this section, the limited data available for correcting for average speed were presented graphically. Recent research, however, resulted in revised speed relationships by model year.[7] To facilitate the presentation, the data are given as equations and appropriate coefficients in Table 3.1.4-2. These relationships were developed by performing five major tasks. First, urban driving pattern data collected during the CAPE-10 Vehicle Operation Survey[13] were processed by city and time of day into freeway, non-freeway, and composite speed-mode matrices. Second, a large number of driving patterns were computer-generated for a range of average speeds (15 to 45 mi/hr; 24 to 72 km/hr) using weighted combinations of freeway and non-freeway matrices. Each of these patterns was filtered for "representativeness." Third, the 88 resulting patterns were input (second by second speeds) to the EPA modal emission analysis model (see 3.1.2-3).[11] The output of the model was estimated emissions for each of 11 vehicle groups (see Table 3.1.4-2 for a listing of these groups). Fourth, a regression analysis was performed to relate estimated emissions to average route speed for each of the 11 vehicle groups. Fifth, these relationships were normalized to 19.6 mi/hr (31.6 km/hr) and summarized in Table 3.1.4-2.

The equations in Table 3.1.4-2 apply only for the range of the data — from 15 to 45 mi/hr (24 to 72 km/hr). Because of the need, in some situations, to estimate emissions at very low average speeds, correction factors have been developed for this purpose. The speed correction factors for 5 and 10 mi/hr (8 and 16 km/hr) presented in Table 3.1.4-3 were developed using a method somewhat like that described above, again using the modal emission model. Because the modal emission model predicts warmed-up vehicle emissions, the use of this model to develop speed correction factors makes the assumption that a given speed correction factor applies equally well to hot and cold vehicle operation.

Temperature Correction Factor (z_{ipt}). The 1975 FTP requires that emission measurements be made within the limits of a relatively narrow temperature band (68 to 86°F). Such a band facilitates uniform testing in laboratories without requiring extreme ranges of temperature control. Present emission factors for motor vehicle are based on data from the standard Federal test (assumed to be at 75°F). Recently, EPA and the Bureau of Mines undertook a test program to evaluate the effect of ambient temperatures on motor vehicle exhaust emissions levels.[9] The study indicates that changes in ambient temperature result in significant changes in emissions during cold start-up operation. Because many Air Quality Control Regions have temperature characteristics differing considerably from the 68 to 86°F range, the temperature correction factor should be applied. The corrections factors are expressed in equational form and presented in Table 3.1.4-5 and can be applied between 20 and 80°F. For temperatures outside this range, the appropriate endpoint correction factor should be applied.

Hot/Cold Vehicle Operation Correction Factor (r_{iptw}). The 1975 FTP measures emissions over three types of driving: a cold transient phase (representative of vehicle start-up after a long engine-off period), a hot transient phase (representative of vehicle start-up after a short engine-off period), and a stabilized phase (representative of warmed-up vehicle operation). The weighting factors used in the 1975 FTP are 20 percent, 27 percent, and 53 percent of total miles (time) in each of the three phases, respectively. Thus, when the 1975 FTP emission factors are applied to a given region for the purpose of assessing air quality, 20 percent of the light-duty trucks in the area of interest are assumed to be operating in a cold condition, 27 percent in a hot start-up condition, and 53 percent in a hot stabilized condition. For non-catalyst equipped vehicles (all pre-1975 model year vehicles), emission in the two hot phases are essentially equivalent on a grams per mile (g/km) basis. Therefore, the 1975 FTP emission factor represents 20 percent cold operation and 80 percent hot operation.

Many situations exist in which the application of these particular weighting factors may be inappropriate. For example, light-duty truck operation in center city areas may have a much higher percentage of cold operation during the afternoon pollutant emissions peak when work-to-home trips are at a maximum and vehicles have been standing for 8 hours. The hot/cold vehicle operation correction factor allows the cold operation phase to range from 0 to 100 percent of total light-duty truck operations. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$r_{iptw} = \frac{w + (100 - w)f(t)}{20 + 80f(t)} \qquad (3.1.4\text{-}2)$$

where: f(t) is given in Table 3.1.4-5

3.1.4.2.2 Crankcase and evaporative hydrocarbon emissions — Evaporative and crankcase hydrocarbon emissions are determined using:

$$f_n = \sum_{i=n-12}^{n} h_i m_{in} \qquad (3.1.4\text{-}3)$$

where: f_n = The combined evaporative and crankcase hydrocarbon emission factor for calendar year (n)

h_i = The combined evaporative and crankcase hydrocarbon emission rate for the i^{th} model year. Emission factors for this source are reported in Table 3.1.4-6. The crankcase and evaporative emissions reported in the table are added together to arrive at this variable.

m_{in} = The weighted annual travel of the i^{th} model year vehicle during calendar year (n)

Table 3.1.4-6. CRANKCASE AND EVAPORATIVE HYDROCARBON EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS
EMISSION FACTOR RATING: B

Location	Model years	Crankcase emissions[a]		Evaporative emissions[b]	
		g/mi	g/km	g/mi	g/km
All areas except high altitude and California[c]	Pre-1963	4.6	2.9	3.6	2.2
	1963-1967	2.4	1.5	3.6	2.2
	1968-1970	0.0	0.0	3.6	2.2
	1971	0.0	0.0	3.1	1.9
	1972	0.0	0.0	3.1	1.9
High altitude	Pre-1963	4.6	2.9	4.6	2.9
	1963-1967	2.4	1.5	4.6	2.9
	1968-1970	0.0	0.0	4.6	2.9
	1971-1972	0.0	0.0	3.9	2.4

[a] Reference 12. Tabulated values were determined by assuming that two-thirds of the light-duty trucks are 6000 lb GVW (2700 kg) and under and that one-third are 6001 to 8500 lb GVW (2700 to 3860 kg).

[b] Light-duty vehicle evaporative data (Section 3.1.2) and heavy-duty vehicle evaporative data (Table 3.1.4-8) were used to estimate the values.

[c] For California: Evaporative emissions for the 1970 model year are 1.9 g/km (3.1 g/mi). All other model years are the same as those reported as "All areas except high altitude and California." Crankcase emissions for the pre-1961 California light-duty trucks are 4.6 g/mi (2.9 g/km) and 1961-1963 models years are 2.4 g/mi (1.5 g/km) all post-1963 model year vehicles are 0.0 g/mi (0.0 g/km).

3.1.4.2.3 Sulfur oxide and particulate emissions – Sulfur oxide and particulate emission factors for all model year light trucks are presented in Table 3.1.4-7. Sulfur oxides factors are based on fuel sulfur content and fuel consumption. Tire-wear particulate factors are based on automobile test results, a premise necessary because of the lack of data. Light truck tire wear is likely to result in greater particulate emissions than automobiles because of larger tires and heavier loads on tires.

Table 3.1.4-7. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS
EMISSION FACTOR RATING: C

Pollutant	Emissions, Pre-1973 vehicles	
	g/mi	g/km
Particulate[a]		
Exhaust	0.34	0.21
Tire wear[b]	0.20	0.12
Sulfur oxides[c] (SO_x as SO_2)	0.18	0.11

[a] References 13 and 14. Based on tests of automobiles.

[b] Reference 14 summarized tests of automotive tire wear particulate. It is assumed that light-duty truck emissions are similar. The automotive tests assume a four-tire vehicle. If corrections for vehicles with a greater number of tires are needed, multiply the above value by the number of tires and divide by four.

[c] Based on an average fuel consumption 10.0 mi/gal (4.3 km/liter) from Reference 15 and on the use of a fuel with a 0.032 percent sulfur content from References 12 and 16 and a density of 6.1 lb/gal (0.73 kg/liter) from References 17 and 18.

3.1.4.3 Heavy-Duty Vehicle Emissions – Emissions research on heavy-duty, gasoline-powered vehicles has been limited in contrast to that for light-duty vehicles and light-duty trucks. As a result, cold operation correction factors, temperature correction factors, speed correction factors, idle emission rates, etc. are not available for heavy-duty vehicles. For some of these variables, however, light-duty vehicle data can be applied to heavy-duty vehicles. In instances in which light-duty vehicle data are not appropriate, a value of unity is assumed.

3.1.4.3.1 Carbon monoxide, hydrocarbon, and nitrogen oxides emissions – The calculation of heavy-duty, gasoline-powered vehicle exhaust emission factors can be accomplished using:

$$e_{nps} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \, v_{ips} \qquad (3.1.4\text{-}4)$$

where: e_{nps} = Composite emission factor in grams per mile (grams per kilometer) for calendar year (n) and pollutant (p) and average speed(s)

c_{ipn} = The test procedure emission rate (Table 3.1.4-8) for pollutant (p) in g/mi (g/km) for the i^{th} model year in calendar year (n)

m_{in} = The weighted annual travel of the i^{th} model year vehicles during calendar year (n). The determination of this variable involves the use of the vehicle year distribution.

v_{ips} = The speed correction factor for the i^{th} model year vehicles for pollutant (p) and average speed(s)

Table 3.1.4-8. EXHAUST EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED TRUCKS FOR CALENDAR YEAR 1972[a]
EMISSION FACTOR RATING: B

Location	Model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides	
		g/mi	g/km	g/mi	g/km	g/mi	g/km
All areas except high altitude	Pre-1970	238	148	35.4	22.0	6.8	4.2
	1970	188	117	13.8	8.6	12.6	7.8
	1971	188	117	13.7	8.5	12.6	7.8
	1972	188	117	13.6	8.4	12.6	7.8
High altitude only[b]	Pre-1970	359	223	48.5	30.2	4.1	2.5
	1970	299	186	15.0	9.3	8.1	5.0
	1971	299	186	14.9	9.3	8.1	5.0
	1972	299	186	14.8	9.2	8.1	5.0

[a] Data from References 19 and 20.

[b] Based on light-duty emissions at high altitude compared with light-duty emissions at low altitudes.

A brief discussion of the variables presented in the above equation is necessary to help clarify their formulation and use. The following paragraphs further describe the variables c_{ipn}, m_{in}, and v_{ips} as they apply to heavy-duty, gasoline-powered vehicles.

Test procedure emission factor (c_{ipn}). The emission factors for heavy-duty vehicles (Table 3.1.4-8) for all areas are based on tests of vehicles operated on-the-road over the San Antonio Road Route (SARR). The SARR, located in San Antonio, Texas, is 7.24 miles long and includes freeway, arterial, and local/collector highway segments.[17] A constant volume sampler is carried on board each of the test vehicles for collection of a proportional part of the exhaust gas from the vehicle. This sample is later analyzed to yield mass emission rates. Because the SAHR is an actual road route, the average speed varies depending on traffic conditions at the time of the test. The average speed tends to be around 18 mi/hr (29 km/hr) with about 20 percent of the time spent at idle. The test procedure emission factor is composed entirely of warmed-up vehicle operation. Based on preliminary analysis of vehicle operation data[6], almost all heavy-duty vehicle operation is under warmed-up conditions.

Weighted annual mileage (m_{in}). The determination of this variable is illustrated in Table 3.1.4-9. For purposes of this illustration, nationwide statistics have been used. Localized data, if available, should be substituted when calculating the variable m_{in} for a specific area under study.

Table 3.1.4-9. SAMPLE CALCULATION OF FRACTION OF GASOLINE POWERED, HEAVY DUTY VEHICLE ANNUAL TRAVEL BY MODEL YEAR[a]

Age, years	Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)	a x b	Fraction of annual travel (m)[c]
1	0.037	19,000	703	0.062
2	0.070	18,000	1,260	0.111
3	0.078	17,000	1,326	0.117
4	0.086	16,000	1,376	0.122
5	0.075	14,000	1,050	0.093
6	0.075	12,000	900	0.080
7	0.075	10,000	750	0.066
8	0.068	9,500	646	0.057
9	0.059	9,000	531	0.047
10	0.053	8,500	451	0.040
11	0.044	8,000	352	0.031
12	0.032	7,500	240	0.021
≥13	0.247	7,000	1,729	0.153

[a] Vehicles in use by model year as of 1972 (Reference 7).
[b] Reference 7.
[c] $m = ab/\Sigma ab$.

Speed correction factor (v_{ips}). Data based on tests of heavy-duty emissions versus average speed are unavailable. In the absence of these data, light-duty vehicle speed correction factors are recommended. The data presented in Tables 3.1.4-10 and Table 3.1.4-11 should be considered as interim heavy-duty vehicle speed correction factors until appropriate data become available.

Table 3.1.4-10. SPEED CORRECTION FACTORS FOR HEAVY-DUTY VEHICLES[a,b]

Location	Model year	$v_{ps} = e^{(A + Bs + Cs^2)}$						$v_{ps} = A + Bs$	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude	Pre-1970	0.953	-6.00×10^{-2}	5.81×10^{-4}	0.967	-6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
	1970-1972	1.070	-6.63×10^{-2}	5.98×10^{-4}	1.047	-6.52×10^{-2}	6.01×10^{-4}	0.888	[illegible]
High altitude	Pre-1970	0.863	-5.98×10^{-2}	5.52×10^{-4}	0.721	-4.57×10^{-2}	4.56×10^{-4}	0.512	2.027×10^{-2}
	1970-1972	0.722	-4.62×10^{-2}	4.80×10^{-4}	0.662	-4.23×10^{-2}	4.23×10^{-4}	0.640	1.835×10^{-2}

[a] Reference 6. Equations should not be extended beyond the range of data (15 to 45 mi/hr). These data are from tests of light-duty vehicles and are assumed applicable to heavy-duty vehicles.

[b] Speed (s) = miles per hour (1 mi/hr = 1.62 km/hr).

Table 3.1.4-11. LOW AVERAGE SPEED CORRECTION FACTORS FOR HEAVY DUTY VEHICLES[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)
Low altitude	Pre-1970	2.72	1.57	2.50	1.45	1.08	1.03
	1970-1972	3.06	1.75	2.96	1.66	1.04	1.00
High altitude	Pre-1970	2.29	1.48	2.34	1.37	1.33	1.20
	1970-1972	2.43	1.54	2.10	1.27	1.22	1.18

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 8) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr; 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data represent the best currently available information for light-duty vehicles. These data are assumed applicable to heavy-duty vehicles given the lack of better information.

For an explanation of the derivation of these factors, see section 3.1.4.3.1.

In addition to exhaust emission factors, the calculation of evaporative and crankcase hydrocarbon emissions are determined using:

$$f_n = \sum_{i=n-12}^{n} h_i m_{in} \qquad (3.1.4\text{-}5)$$

where: f_n = The combined evaporative and crankcase hydrocarbon emission factor for calendar year (n)

h_i = The combined evaporative and crankcase hydrocarbon emission rate for the ith model year. Emission factors for this source are reported in Table 3.1.4-12.

m_{in} = The weighted annual travel of the ith model year vehicle during calendar year (n)

Table 3.1.4-12. CRANKCASE AND EVAPORATIVE HYDROCARBON EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED VEHICLES

EMISSION FACTOR RATING: B

Location	Model years	Crankcase hydrocarbon[a]		Evaporative hydrocarbons[b]	
		g/mi	g/km	g/mi	g/km
All areas except high altitude and California	Pre-1968	5.7	3.5	5.8	3.6
	1968-1972	0.0	0.0	5.8	3.6
California only	Pre-1964	5.7	3.5	5.8	3.6
	1964-1972	0.0	0.0	5.8	3.6
High altitude	Pre-1968	5.7	3.5	7.4	4.6
	1968-1972	0.0	0.0	7.4	4.6

[a] Crankcase factors are from Reference 12.

[b] References 1, 21, and 22 were used to estimate evaporative emission factors for heavy-duty vehicles. Equation 3.1.2-6 was used to calculate g/mi (g/km) values (evaporative emission factor = g + kd). The heavy-duty vehicle diurnal evaporative emissions (g) were assumed to be three times the light-duty vehicle value to account for the larger size fuel tanks used on heavy-duty vehicles. Nine trips per day (d = number of trips per day) from Reference 8 were used in conjunction with the light-duty vehicle hot soak emissions (k) to yield a total evaporative emission rate in grams per day. This value was divided by 36.2 mi/day (58.3 km/day) from Reference 7 to obtain the per mile (per kilometer) rate.

3.1.4.3.2 Sulfur oxide and particulate emissions – Sulfur oxide and particulate emission factors for all model year heavy-duty vehicles are presented in Table 3.1.4-13. Sulfur oxides factors are based on fuel sulfur content and fuel consumption. Tire-wear particulate factors are based on automobile test results – a premise necessary because of the lack of data. Truck tire wear is likely to result in greater particulate emissions than automobiles because of larger tires, heavier loads on tires, and more tires per vehicle. Although the factors presented in Table 3.1.4-13 can be adjusted for the number of tires per vehicle, adjustments cannot be made to account for the other differences.

Table 3.1.4-13. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED VEHICLES
EMISSION FACTOR RATING: B

Pollutant	Emissions	
	g/mi	g/km
Particulate		
Exhaust[a]	0.91	0.56
Tire wear[b]	0.20T	0.12T
Sulfur oxides[c] (SO_x as SO_2)	0.36	0.22

[a] Calculated from the Reference 13 value of 12 lb/10^3 gal (1.46 g/liter) gasoline. A 6.0 mi/gal (2.6 km/liter) value from Reference 23 was used to convert to a per kilometer (per mile) emission factor.

[b] Reference 14. The data from this reference are for passenger cars. In the absence of specific data for heavy-duty vehicles, they are assumed to be representative of truck tire wear particulate. An adjustment is made for trucks with more than four tires. T equals the number of tires divided by four.

[c] Based on an average fuel consumption of 6.0 mi/gal (2.6 km/liter) from Reference 23, on a 0.04 percent sulfur content from Reference 16 and 17, and on a density of 6.1 lb/gal (0.73 kg/liter) from References 16 and 17.

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3.1.5 Heavy-Duty, Diesel-Powered Vehicles

revised by David S. Kircher
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3.1.5.1 General[1,2] — On the highway, heavy-duty diesel engines are primarily used in trucks and buses. Diesel engines in any application demonstrate operating principles that are significantly different from those of the gasoline engine.

3.1.5.2 Emissions — Diesel trucks and buses emit pollutants from the same sources as gasoline-powered vehicles: exhaust, crankcase blow-by, and fuel evaporation. Blow-by is practically eliminated in the diesel, however, because only air is in the cylinder during the compression stroke. The low volatility of diesel fuel along with the use of closed injection systems essentially eliminates evaporation losses in diesel systems.

Exhaust emissions from diesel engines have the same general characteristics of auto exhausts. Concentrations of some of the pollutants, however, may vary considerably. Emissions of sulfur dioxide are a direct function of the fuel composition. Thus, because of the higher average sulfur content of diesel fuel (0.20 percent S) as compared with gasoline (0.035 percent S), sulfur dioxide emissions are relatively higher from diesel exhausts.[3,4]

Because diesel engines allow more complete combustion and use less volatile fuels than spark-ignited engines, their hydrocarbon and carbon monoxide emissions are relatively low. Because hydrocarbons in diesel exhaust represent largely unburned diesel fuel, their emissions are related to the volume of fuel sprayed into the combustion chamber. Both the high temperature and the large excesses of oxygen involved in diesel combustion are conducive to high nitrogen oxide emission, however.[5]

Particulates from diesel exhaust are in two major forms — black smoke and white smoke. White smoke is emitted when the fuel droplets are kept cool in an environment abundant in oxygen (cold starts). Black smoke is emitted when the fuel droplets are subjected to high temperatures in an environment lacking in oxygen (road conditions).

Emissions from heavy-duty diesel vehicles during a calendar year (n) and for a pollutant (p) can be approximately calculated using:

$$e_{nps} = \sum_{i=n-12}^{n} c_{ipn} s_{ips} \qquad (3.1.5\text{-}1)$$

where:

e_{nps} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), and average speed (s)

c_{ipn} = The emission rate in g/mi (g/km) for the i^{th} model year vehicles in calendar year (n) over a transient urban driving schedule with an average speed of approximately 18 mi/hr (29 km/hr)

s_{ips} = The speed correction factor for the i^{th} model year heavy-duty diesel vehicles for pollutant (p) and average speed (s)

Values for c_{ipn} are given in Table 3.1.5-1. These emission factors are based on tests of vehicles on the road over the San Antonio Road Route (SARR). The SARR, located in San Antonio, Texas, is 7.24 miles long and includes freeway, arterial, and local/collector highway segments.[7] A constant volume sampler is carried on board each test vehicle for collection of a proportional part of the vehicle's exhaust. This sample is later analyzed to yield mass emission rates. Because the SARR is an actual road route, the average speed varies depending on traffic conditions at the time of the test. The average speed, however, tends to be around 18 mi/hr (29 km/hr) with about 20 percent of the time spent at idle. The test procedure emission factor is composed entirely of warmed-up vehicle operation. Based on a preliminary analysis of vehicle operation data, heavy-duty vehicles operate primarily (about 95 percent) in a warmed-up condition.

Table 3.1.5-1. EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED VEHICLES (ALL PRE-1973 MODEL YEARS) FOR CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Pollutant	Truck emissions[a]		City bus emissions[b]	
	g/mi	g/km	g/mi	g/km
Particulate[c]	1.3	0.81	1.3	0.81
Sulfur oxides[c,d] (SO_x as SO_2)	2.8	1.7	2.8	1.7
Carbon monoxide	28.7	17.8	21.3	13.2
Hydrocarbons	4.6	2.9	4.0	2.5
Nitrogen oxides (NO_x as NO_2)	20.9	13.0	21.5	13.4
Aldehydes[c] (as HCHO)	0.3	0.2	0.3	0.2
Organic acids[c]	0.3	0.2	0.3	0.2

[a] Truck emissions are based on over-the-road sampling of diesel trucks by Reference 7. Sampling took place on the San Antonio (Texas) Road Route (SARR), which is 7.24 miles (11.7 kilometers) long and includes freeway, arterial, and local-collector highway segments. Vehicles average about 18 mi/hr (29 km/hr) over this road route.

[b] Bus emission factors are also based on the SARR. 13-Mode emission data from Reference 8 were converted to SARR values using cycle-to-cycle conversion factors from Reference 8.

[c] Reference 6. Tire wear particulate not included in above particulate emission factors. See tire wear particulate, heavy-duty gasoline section.

[d] Data based on assumed fuel sulfur content of 0.20 percent. A fuel economy of 4.6 mi/gal (2.0 km/liter) was used from Reference 8.

The speed correction factor, v_{ps}, can be computed using data in Table 3.1.5-2. Table 3.1.5-2 gives heavy-duty diesel HC, CO, and NO_x emission factors in grams per minute for the idle mode, an urban transient mode with average speed of 18 mi/hr (29 km/hr), and an over-the-road mode with an average speed of approximately 60 mi/hr (97 km/hr). For average speeds less than 18 mi/hr (29 km/hr) the correction factor is:

$$v_{ps} = \frac{\text{Urban} + \left(\frac{18}{S} - 1\right)\text{Idle}}{\text{Urban}} \qquad (3.1.5\text{-}2)$$

where: S is the average speed of interest (in mi/hr), and the urban and idle values (in g/min) are obtained from Table 3.1.5-2. For average speeds above 18 mi/hr (29 km/hr), the correction factor is:

$$v_{ps} = \frac{\frac{18}{42S}\left[(60-S)\text{Urban} + (S-18)\text{Over the Road}\right]}{\text{Urban}} \qquad (3.1.5\text{-}3)$$

Where: S is the average speed (in mi/hr) of interest. Urban and over-the-road values (in g/min) are obtained from Table 3.1.5-2. Emission factors for heavy-duty diesel vehicles assume all operation to be under warmed-up vehicle conditions. Temperature correction factors, therefore, are not included because ambient temperature has minimal effect on warmed-up operation.

Table 3.1.5-2. EMISSION FACTORS FOR HEAVY-DUTY DIESEL VEHICLES
UNDER DIFFERENT OPERATING CONDITIONS
EMISSION FACTOR RATING: B

Pollutant	Emission factors,[a] g/min		
	Idle	Urban [18 mi/hr (29 km/hr)]	Over the road [60 mi/hr (97 km/hr)]
Carbon monoxide	0.64	8.61	5.40
Hydrocarbons	0.32	1.38	2.25
Nitrogen oxides (NO_x as NO_2)	1.03	6.27	28.3

[a] Reference 7. Computed from data contained in the reference.

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3.1.6 Gaseous-Fueled Vehicles

by David S. Kircher

3.1.6.1 General. – Conversion of vehicles to gaseous fuels has been practiced for many years. In the past the principal motivation for the conversion has been the economic advantage of gaseous fuels over gasoline rather than lower air pollutant emission levels that result from their use. Recently, however, conversions have been made for air pollution control as well as for lower operating cost. Liquified petroleum gas (LPG), the most common form of gaseous fuel for vehicles, is currently used to power approximately 300,000 vehicles in the United States. Natural gas, in the form of compressed natural gas (CNG) or liquified natural gas (LNG), is being used nationally to power about 4,000 vehicles.[1] Of the two natural gas fuels, CNG is the most common. Natural gas conversions are usually dual fuel systems that permit operation on either gaseous fuel (CNG or LNG) or gasoline.

3.1.6.2 Emissions. – Tables 3.1.6-1 and 3.1.6-2 contain emission factors for light- and heavy-duty vehicles converted for either gaseous fuel or dual fuel operation. The test data used to determine the average light-duty emission factors were based on both the 1972 Federal test procedure and the earlier seven-mode method.[7,8] These test data were converted to the current Federal test procedure[9] using conversion factors determined empirically.[10,11] This conversion was necessary to make the emission factors for these vehicles consistent with emission factors reported in previous sections of this chapter.

Heavy-duty vehicle emission factors (Table 3.1.6-2) are based on tests of vehicles on an experimental dynamometer test cycle[6] and on the Federal test procedure. Emissions data for heavy-duty vehicles are limited to tests of only a few vehicles. For this reason the factors listed in table 3.1.6-2 are only approximate indicators of emissions from these vehicles.

Emission data on gaseous-powered vehicles are limited to dynamometer test results. Deterioration factors and speed correction factors are not available. The data contained in the tables, therefore, are emission factors for in-use vehicles at various mileages rather than emission rates (as defined in section 3.1.2).

Emission factors for a particular population of gaseous-fueled vehicles can be determined using the relationship:

$$e_{npwc} = \sum_{i=n-12}^{n+1} c_i f_i \tag{1}$$

where: e_{npwc} = Emission factor is grams per mile (or g/km) for calendar year (n), pollutant (p), vehicle weight (w) (light- or heavy-duty), and conversion fuel system (c) (e.g. LPG)

c_i = The test cycle emission factor (Tables 3.1.6-1 and 3.1.6-2) for pollutant (p) for the i^{th} model year vehicles

f_i = The fraction of total miles driven by a population of gaseous-fueled vehicles that are driven by the i^{th} model year vehicles

Carbon monoxide, hydrocarbon, and nitrogen oxides emission factors are listed in the tables. Particulates and sulfur oxides are not listed because of the lack of test data. Because stationary external combustion of gaseous fuel results in extremely low particulate and sulfur oxides, it is reasonable to assume that the emissions of these pollutants from gaseous-fueled vehicles are negligible.

Table 3.1.6-1. EMISSION FACTORS BY MODEL YEAR FOR LIGHT-DUTY VEHICLES USING LPG, LPG/DUAL FUEL, OR CNG/DUAL FUEL[a]

EMISSION FACTOR RATING: B

Fuel and model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides (NO_x as NO_2)	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
LPG						
Pre-1970[b]	11	6.8	1.8	1.1	3.2	2.0
1970 through 1972[c]	3.4	2.1	0.67	0.42	2.8	1.7
LPG/Dual fuel[d]						
Pre-1973	7.8	4.8	2.4	1.5	3.4	2.1
CNG/Dual fuel[e]						
Pre-1973	9.2	5.7	1.5	0.93	2.8	1.7

[a] References 1 through 5.

[b] Emission factors are based on tests of 1968 and 1969 model year vehicles. Sufficient data for earlier models are not available.

[c] Based on tests of 1970 model year vehicles. No attempt was made to predict the emissions resulting from the conversion of post-1974 model year vehicles to gaseous fuels. It is likely that 1973 and 1974 model year vehicles converted to gaseous fuels will emit pollutant quantities similar to those emitted by 1972 vehicles with the possible exception of nitrogen oxides.

[d] The dual fuel system represents certain compromises in emission performance to allow the flexibility of operation on gaseous or liquid (gasoline) fuels. For this reason their emission factors are listed separately from vehicles using LPG only.

[e] Based on tests of 1968 and 1969 model year vehicles. It is likely that 1973 and 1974 model year vehicles will emit similar pollutant quantities to those listed with the possible exception of nitrogen oxides. No attempt was made to estimate 1975 and later model year gaseous fueled vehicle emissions.

Table 3.1.6-2. EMISSION FACTORS FOR HEAVY-DUTY VEHICLES USING LPG OR CNG/DUAL FUEL

EMISSION FACTOR RATING: C

Pollutant	Emissions (all model years)[a]			
	LPG[b,c]		CNG/dual fuel[d]	
	g/mi	g/km	g/mi	g/km
Carbon monoxide	4.2	2.6	7.5	4.6
Exhaust hydrocarbons	2.4	1.5	2.2	1.4
Nitrogen oxides (NO_x as NO_2)	2.8	1.7	5.8	3.6

[a] Test results are for 1969 through 1970 model years. These results are assumed to apply to all future heavy-duty vehicles based on present and future emission standards.

[b] References 2 and 4.

[c] LPG values for heavy-duty vehicles are based on a limited number of tests of vehicles tuned for low emissions. Vehicles converted to LPG solely for economic reasons gave much higher emission values. For example, eleven vehicles (1950 through 1963) tested in Reference 6 demonstrated average emissions of 160 g/mi (99 g/km) of carbon monoxide, 8.5 g/mi (5.3 g/km) of hydrocarbons, and 4.2 g/mi (2.6 g/km) of nitrogen oxides.

[d] Reference 6.

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3.1.7 Motorcycles

by David S. Kircher

3.1.7.1 General   Motorcycles, which are not, generally, considered an important source of air pollution, have become more popular and their numbers have been steadily increasing in the last few years. Sales grew at an annual rate of 20 percent from 1965 to 1971.[1] The majority of motorcycles are powered by either 2- or 4-stroke, air-cooled engines; however, water-cooled motorcycles and Wankel-powered motorcycles have recently been introduced. Until recently the predominant use of 4-stroke motorcycles was on-highway and the 2-stroke variety was off-highway. This difference in roles was primarily a reflection of significant weight and power variations between available 2- and 4-stroke vehicles. As light-weight 4-strokes and more powerful 2-strokes become available the relative number of motorcycles in each engine category may change. Currently the nationwide population of motorcycles is approximately 38 percent 2-stroke and 62 percent 4-stroke. Individual motorcycles travel, on the average, approximately 4000 miles per year.[1] These figures, along with registration statistics, enable the rough estimation of motorcycle miles by engine category and the computation of resulting emissions.

3.1.7.2 Emissions   The quantity of motorcycle emission data is rather limited in comparison with the data available on other highway vehicles. For instance, data on motorcycle average speed versus emission levels are not available. Average emission factors for motorcycles used on highways are reported in Table 3.1.7-1. These data, from several test vehicles, are based on the Federal light-duty vehicle test procedure.[2] The table illustrates differences in 2-stroke and 4-stroke engine emission rates. On a per mile basis, 2-stroke engines emit nearly five times more hydrocarbons than 4-stroke engines. Both engine categories emit somewhat similar quantities of carbon monoxide and both produce low levels of nitrogen oxides.

Table 3.1.7-1. EMISSION FACTORS FOR MOTORCYCLES[a]
EMISSION FACTOR RATING: B

Pollutant	Emissions			
	2-stroke engine		4-stroke engine	
	g/mi	g/km	g/mi	g/km
Carbon monoxide	27	17	33	20
Hydrocarbons				
Exhaust	16	9.9	2.9	1.8
Crankcase[b]			0.60	0.37
Evaporative[c]	0.36	0.22	0.36	0.22
Nitrogen oxides (NO_x as NO_2)	0.12	0.075	0.24	0.15
Particulates	0.33	0.21	0.046	0.029
Sulfur oxides[d] (SO_2)	0.038	0.024	0.022	0.014
Aldehydes (RCHO as HCHO)	0.11	0.068	0.047	0.029

[a] Reference 1.

[b] Most 2-stroke engines use crankcase induction and produce no crankcase losses.

[c] Evaporative emissions were calculated assuming that carburetor losses were negligible. Diurnal breathing of the fuel tank (a function of fuel vapor pressure, vapor space in the tank, and diurnal temperature variation) was assumed to account for all the evaporative losses associated with motorcycles. The value presented is based on average vapor pressure, vapor space, and temperature variation.

[d] Calculated using a 0.043 percent sulfur content (by weight) for regular fuel used in 2-stroke engines and 0.022 percent sulfur content (by weight) for premium fuel used in 4-stroke engines.

References for Section 3.1.7

1. Hare, C.T. and K.J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part III, Motorcycles. Final Report. Southwest Research Institute. San Antonio, Texas. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHS 70-108. March 1973.

2. Exhaust Emission Standards and Test Procedures. Federal Register. 36(128):12652-12663, July 2, 1971.

3.2 OFF-HIGHWAY, MOBILE SOURCES

The off-highway category of internal combustion engines embraces a wide range of mobile and semimobile sources. Emission data are reported in this section on the following sources: aircraft; locomotives; vessels (inboard and outboard); and small general utility engines, such as those used in lawnmowers and minibikes. Other sources that fall into this category, but for which emission data are not currently available, include: snowmobiles, all-terrain vehicles, and farm and construction equipment. Data on these sources will be added to this chapter in future revisions.

3.2.1 Aircraft

by Charles C. Masser

3.2.1.1 General – Aircraft engines are of two major categories: reciprocating (piston) and gas turbine.

The basic element in the aircraft piston engine is the combustion chamber, or cylinder, in which mixtures of fuel and air are burned and from which energy is extracted through a piston and crank mechanism that drives a propeller. The majority of aircraft piston engines have two or more cylinders and are generally classified according to their cylinder arrangement – either "opposed" or "radial." Opposed engines are installed in most light or utility aircraft; radial engines are used mainly in large transport aircraft.

The gas turbine engine in general consists of a compressor, a combustion chamber, and a turbine. Air entering the forward end of the engine is compressed and then heated by burning fuel in the combustion chamber. The major portion of the energy in the heated air stream is used for aircraft propulsion. Part of the energy is expended in driving the turbine, which in turn drives the compressor. Turbofan and turboshaft engines use energy from the turbine for propulsion; turbojet engines use only the expanding exhaust stream for propulsion.

The aircraft classification system used is listed in Table 3.2.1-1. Both turbine aircraft and piston engine aircraft have been further divided into sub-classes depending on the size of the aircraft and the most commonly used engine for that class. Jumbo jets normally have approximately 40,000 pounds maximum thrust per engine, and medium-range jets have about 14,000 pounds maximum thrust per engine. For piston engines, this division is more pronounced. The large transport piston engines are in the 500 to 3,000 horsepower range, whereas the small piston engines develop less than 500 horsepower.

Table 3.2.1-1. AIRCRAFT CLASSIFICATION

Aircraft class	Representative aircraft	Engines per aircraft	Engine commonly used
Jumbo jet	Boeing 747	4	Pratt & Whitney JT-9D
	Lockheed L-1011	3	
	McDonald Douglas DC-10	3	
Long-range jet	Boeing 707	4	Pratt & Whitney JT-3D
	McDonald Douglas DC-8	4	
Medium-range jet	Boeing 727	3	Pratt & Whitney JT-8D
	Boeing 737	2	
	McDonald Douglas DC-9	2	
Air carrier turboprop	Convair 580	2	Allison 501-D13
	Electra L-188	4	
	Fairchild Hiller FH-227	2	
Business jet	Gates Learjet	2	General Electric CJ610 Pratt & Whitney JT-12A
	Lockheed Jetstar	4	
General aviation turboprop	–	–	Pratt & Whitney PT-6A
General aviation piston	Cessna 210	1	Teledyne-Continental Ø-200 Lycoming Ø-320
	Piper 32-300	1	
Piston transport	Douglas DC-6	4	Pratt & Whitney R-2800
Helicopter	Sikorsky S-61	2	General Electric CT-58
	Vertol 107	2	
Military transport			Allison T56A7
Military jet			General Electric J-79 Continental J-69
Military piston			Curtiss-Wright R-1820

3.2.1.2 Landing and Takeoff Cycle - A landing-takeoff (LTO) cycle includes all normal operation modes performed by an aircraft between the time it descends through an altitude of 3,500 feet (1,100 meters) on its approach and the time it subsequently reaches the 3,500 feet (1,100 meters) altitude after take-off. It should be made clear that the term "operation" used by the Federal Aviation Administration to describe either a landing or a takeoff is not the same as the LTO cycle. Two operations are involved in one LTO cycle. The LTO cycle incorporates the ground operations of idle, taxi, landing run, and takeoff run and the flight operations of takeoff and climbout to 3,500 feet (1,100 meters) and approach from 3,500 feet (1,100 meters) to touchdown.

Each class of aircraft has its own typical LTO cycle. In order to determine emissions, the LTO cycle is separated into five distinct modes: (1) taxi-idle, (2) takeoff, (3) climbout, (4) approach and landing, and (5) taxi-idle. Each of these modes has its share of time in the LTO cycle. Table 3.2.1-2 shows typical operating time in each mode for the various types of aircraft classes during periods of heavy activity at a large metropolitan airport. Emissions factors for the complete LTO cycle presented in Table 3.2.1-3 were determined using the typical times shown in Table 3.2.1-2.

Table 3.2.1-2. TYPICAL TIME IN MODE FOR LANDING TAKEOFF CYCLE AT A METROPOLITAN AIRPORT[a]

Aircraft	Time in mode, minutes				
	Taxi-idle	Takeoff	Climbout	Approach	Taxi-idle
Jumbo jet	19.00	0.70	2.20	4.00	7.00
Long range jet	19.00	0.70	2.20	4.00	7.00
Medium range jet	19.00	0.70	2.20	4.00	7.00
Air carrier turboprop	19.00	0.50	2.50	4.50	7.00
Business jet	6.50	0.40	0.50	1.60	6.50
General aviation turboprop	19.00	0.50	2.50	4.50	7.00
General aviation piston	12.00	0.30	4.98	6.00	4.00
Piston transport	6.50	0.60	5.00	4.60	6.50
Helicopter	3.50	0	6.50	6.50	3.50
Military transport	19.00	0.50	2.50	4.50	7.00
Military jet	6.50	0.40	0.50	1.60	6.50
Military piston	6.50	0.60	5.00	4.60	6.50

[a] References 1 and 2.

Table 3.2.1-3. EMISSION FACTORS PER AIRCRAFT LANDING-TAKEOFF CYCLE[a,b]

(lb/engine and kg/engine)

EMISSION FACTOR RATING: B

Aircraft	Solid particulates[c]		Sulfur oxides[d]		Carbon monoxide[e]		Hydrocarbons[e]		Nitrogen oxides[e] (NO_x as NO_2)	
	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg
Jumbo jet	1.30	0.59	1.82	0.82	46.8	21.2	12.2	5.5	31.4	14.2
Long range jet	1.21	0.55	1.56	0.71	47.4	21.5	41.2	18.7	7.9	3.6
Medium range jet	0.41	0.19	1.01	0.46	17.0	7.71	4.9	2.2	10.2	4.6
Air carrier turboprop	1.1	0.49	0.40	0.18	6.6	3.0	2.9	1.3	2.5	1.1
Business jet	0.11	0.05	0.37	0.17	15.8	7.17	3.6	1.6	1.6	0.73
General aviation turboprop	0.20	0.09	0.18	0.08	3.1	1.4	1.1	0.5	1.2	0.54
General aviation piston	0.02	0.01	0.014	0.006	12.2	5.5	0.40	0.18	0.047	0.021
Piston transport	0.56	0.25	0.28	0.13	304.0	138.0	40.7	18.5	0.40	0.18
Helicopter	0.25	0.11	0.18	0.08	5.7	2.6	0.52	0.24	0.57	0.26
Military transport	1.1	0.49	0.41	0.19	5.7	2.6	2.7	1.2	2.2	1.0
Military jet	0.31	0.14	0.76	0.35	15.1	6.85	9.93	4.5	3.29	1.49
Military piston[f]	0.28	0.13	0.14	0.06	152.0	69.0	20.4	9.3	0.20	0.09

[a] References 1 through 5.

[b] Emission factors based on typical times in mode shown in Table 3.2.1-2.

[c] References 1 and 5.

[d] Based on 0.05 percent sulfur content fuel.

[e] References 1, 2, and 4.

[f] Engine emissions based on Pratt & Whitney R-2800 engine scaled down two times.

3.2.1.3 Modal Emission Factors – In Table 3.2.1-4 a set of modal emission factors by engine type are given for carbon monoxide, total hydrocarbons, nitrogen oxides, and solid particulates along with the fuel flow rate per engine for each LTO mode. With this data and knowledge of the time-in-mode, it is possible to construct any LTO cycle or mode and calculate a more accurate estimate of emissions for the situation that exists at a specific airport. This capability is especially important for estimating emissions during the taxi-idle mode when large amounts of carbon monoxide and hydrocarbons are emitted. At smaller commercial airports the taxi-idle time will be less than at the larger, more congested airports.

Table 3.2.1-4. MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

	Fuel rate		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)		Solid particulates	
Engine and mode	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
Pratt & Whitney JT8D										
(Jumbo jet)										
Taxi-idle	1,738	788	102.0	46.3	27.3	12.4	6.06	2.75	2.2	1.0
Takeoff	17,052	7,735	8.29	3.76	2.95	1.34	720.0	327.0	3.75	1.7
Climbout	14,317	6,494	11.7	5.31	2.65	1.20	459.0	208.0	4.0	1.8
Approach	5,204	2,361	32.6	14.8	3.00	1.36	54.7	24.5	2.3	1.0
General Electric CF6										
(Jumbo jet)										
Taxi-idle	1,030	467	51.7	23.5	15.4	7.0	3.6	1.63	0.04	0.02
Takeoff	13,449	6,100	6.7	3.04	1.3	0.59	540.0	245.0	0.54	0.24
Climbout	11,400	5,171	6.6	2.99	1.3	0.59	333.0	151.0	0.54	0.24
Approach	6,204	2,814	18.6	8.44	1.9	0.86	173.0	78.5	0.44	0.20
Pratt & Whitney JT3D										
(Long range jet)										
Taxi-idle	872	396	109.0	49.4	98.6	44.7	1.42	0.645	0.48	0.22
Takeoff	10,835	4,915	12.3	5.60	4.65	2.11	148.0	67.1	8.25	3.7
Climbout	8,956	4,062	15.3	6.94	4.92	2.23	94.2	42.6	8.5	3.9
Approach	4,138	1,877	39.7	18.0	7.84	3.56	21.8	9.89	8.0	3.6
Pratt & Whitney JT3C										
(Long range jet)										
Taxi-idle	1,198	543	92.6	42.0	92.2	41.8	2.49	1.13	0.40	0.18
Takeoff	10,183	4,619	9.04	4.10	0.855	0.388	119.0	54.0	6.50	2.9
Climbout	8,509	3,860	3.88	1.76	0.892	0.405	64.7	29.4	6.25	2.8
Approach	4,115	1,867	49.0	22.2	8.26	3.75	23.2	10.5	3.35	1.5
Pratt & Whitney JT4A										
(Long range jet)										
Taxi-idle	1,389	630	62.8	28.5	64.8	29.4	2.71	1.23	1.2	0.54
Takeoff	15,511	7,036	1.15	0.52	0.674	0.306	236.0	107.0	21.0	9.5
Climbout	12,141	5,507	18.1	8.20	1.27	0.576	155.0	70.3	2.5	1.1
Approach	5,964	2,705	26.3	11.9	3.83	1.74	35.9	16.3	6.0	2.7

Table 3.2.1-4 (continued). MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

Engine and mode	Fuel		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NOx as NO2)		Solid particulates	
	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
General Electric										
CJ805										
[illegible]										
Taxi-idle	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.57	0.712	1.3	0.59
Takeoff	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15.0	6.8
Climbout	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15.0	6.8
Approach	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.0	2.3
Pratt & Whitney										
JT8D										
(Mil. transport)										
Taxi-idle	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.36	0.16
Takeoff	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.7	1.7
Climbout	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6	1.2
Approach	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.5	0.68
Rolls Royce										
Spey RB163										
(Mil. transport)										
Taxi-idle	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Takeoff	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.0	7.3
Climbout	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.0	4.5
Approach	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.5	0.68
Allison T56-A15										
(Air carrier										
turboprop,										
mil. trans-										
port)										
Taxi-idle	493	224	8.74	3.96	7.39	3.35	1.23	0.560	1.6	0.73
Takeoff	2,393	1,085	3.77	1.71	0.440	0.200	27.9	12.7	3.7	1.7
Climbout	2,188	992	3.40	1.54	0.288	0.131	22.2	10.1	3.0	1.4
Approach	1,145	520	3.49	1.58	0.326	0.148	7.32	3.32	3.0	1.4
Allison T56-A7										
(Air carrier										
turboprop,										
mil. trans-										
port)										
Taxi-idle	548	249	15.3	6.94	6.47	2.93	2.16	0.980	1.6	0.73
Takeoff	2,079	943	2.15	0.975	0.430	0.195	22.9	10.4	3.7	1.7
Climbout	1,908	865	3.01	1.37	0.476	0.216	21.2	9.62	3.0	1.4
Approach	1,053	478	3.67	1.66	0.517	0.235	7.78	3.53	3.0	1.4

Table 3.2.1-4 (continued). MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

	Fuel rate		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)		Solid particulates	
Engine and mode	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
Airesearch TPE 331[d] (Gen. aviation turboprop)										
Taxi-idle	146	66.2	3.53	1.60	0.630	0.286	0.955	0.433	0.3	0.14
Takeoff	365	166.0	0.393	0.178	0.055	0.025	3.64	1.65	0.8	0.36
Climbout	339	154.0	0.565	0.256	0.052	0.024	3.31	1.50	0.6	0.27
Approach	206	93.4	2.58	1.17	0.240	0.109	1.69	0.767	0.6	0.27
Teledyne/Continental 0-200 (Gen. aviation piston)										
Taxi-idle	7.68	3.48	7.52	3.41	0.214	0.097	0.009	0.004	NA[e]	NA
Takeoff	48.4	22.0	54.6	24.8	0.720	0.327	0.259	0.117	NA	NA
Climbout	48.4	22.0	54.6	24.8	0.720	0.327	0.259	0.117	NA	NA
Approach	21.3	9.66	22.8	10.3	0.380	0.172	0.052	0.024	NA	NA
Lycoming 0-320 (Gen. aviation piston)										
Taxi-idle	13.0	5.90	11.1	5.03	0.355	0.161	0.013	0.006	NA	NA
Takeoff	65.7	29.8	70.9	32.2	1.49	0.676	0.214	0.097	NA	NA
Climbout	63.5	28.8	65.8	29.8	1.31	0.594	0.375	0.170	NA	NA
Approach	23.1	10.5	24.3	11.0	0.496	0.225	0.051	0.023	NA	NA

[a] References 4 and 5.
[b] Estimated and/or calculated.
[c] "Dirtied smokeless" JT-8D. All air carriers scheduled for conversion of JT-8D engines to smokeless by January 1973.
[d] Similar to the PT-6A engine.
[e] NA: Not available.

References for Section 3.2.1

1. Nature and Control of Aircraft Engine Exhaust Emissions. Northern Research and Engineering Corporation, Cambridge, Mass. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number PH22-68-27. November 1968.

2. The Potential Impact of Aircraft Emissions upon Air Quality. Northern Research and Engineering Corporation, Cambridge, Mass. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number 68-02-0085. December 1971.

3. Assessment of Aircraft Emission Control Technology. Northern Research and Engineering Corporation, Cambridge, Mass. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number 68-04-0011. September 1971.

4. Analysis of Aircraft Exhaust Emission Measurements. Cornell Aeronautical Laboratory Inc., Buffalo, N.Y. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number 68-04-0040. October 1971.

5. Private communication with Dr. E. Karl Bastress. IKOR Incorporated, Burlington, Mass. November 1972.

3.2.2 Locomotives

by David S. Kircher

3.2.2.1 General – Railroad locomotives generally follow one of two use patterns: railyard switching or road-haul service. Locomotives can be classified on the basis of engine configuration and use pattern into five categories: 2-stroke switch locomotive (supercharged), 4-stroke switch locomotive, 2-stroke road service locomotive (supercharged), 2-stroke road service locomotive (turbocharged), and 4-stroke road service locomotive.

The engine duty cycle of locomotives is much simpler than many other applications involving diesel internal combustion engines because locomotives usually have only eight throttle positions in addition to idle and dynamic brake. Emission testing is made easier and the results are probably quite accurate because of the simplicity of the locomotive duty cycle.

3.2.2.2 Emissions – Emissions from railroad locomotives are presented two ways in this section. Table 3.2.2-1 contains average factors based on the nationwide locomotive population breakdown by category. Table 3.2.2-2 gives emission factors by locomotive category on the basis of fuel consumption and on the basis of work output (horsepower hour).

The calculation of emissions using fuel-based emission factors is straightforward. Emissions are simply the product of the fuel usage and the emission factor. In order to apply the work output emission factor, however, an

Table 3.2.2-1. AVERAGE LOCOMOTIVE EMISSION FACTORS BASED ON NATIONWIDE STATISTICS[a]

Pollutant	Average emissions[b]	
	lb/10^3 gal	kg/10^3 liter
Particulates[c]	25	3.0
Sulfur oxides[d] (SO_x as SO_2)	57	6.8
Carbon monoxide	130	16
Hydrocarbons	94	11
Nitrogen oxides (NO_x as NO_2)	370	44
Aldehydes (as HCHO)	5.5	0.66
Organic acids[c]	7	0.84

[a] Reference 1.

[b] Based on emission data contained in Table 3.2.2-2 and a breakdown of locomotive use by engine category in the United States in Reference 1.

[c] Data based on highway diesel data from Reference 2. No actual locomotive particulate test data are available.

[d] Based on a fuel sulfur content of 0.4 percent from Reference 3.

Table 3.2.2-2. EMISSION FACTORS BY LOCOMOTIVE ENGINE CATEGORY[a]
EMISSION FACTOR RATING: B

Pollutant	Engine category				
	2-Stroke supercharged switch	4-Stroke switch	2-Stroke supercharged road	2-Stroke turbocharged road	4-Stroke road
Carbon monoxide					
lb/10^3 gal	84	380	66	160	180
kg/10^3 liter	10	46	7.9	19	22
g/hphr	3.9	13	1.8	4.0	4.1
g/metric hphr	3.9	13	1.8	4.0	4.1
Hydrocarbon					
lb/10^3 gal	190	146	148	28	99
kg/10^3 liter	23	17	18	3.4	12
g/hphr	8.9	5.0	4.0	0.70	2.2
g/metric hphr	8.9	5.0	4.0	0.70	2.2
Nitrogen oxides (NO_x as NO_2)					
lb/10^3 gal	250	490	350	330	470
kg/10^3 liter	30	59	42	40	56
g/hphr	11	17	9.4	8.2	10
g/metric hphr	11	17	9.4	8.2	10

[a] Use average factors (Table 3.2.2-1) for pollutants not listed in this table.

additional calculation is necessary. Horsepower hours can be obtained using the following equation:

$$w = lph$$

where:

w = Work output (horsepower hour)

l = Load factor (average power produced during operation divided by available power)

p = Available horsepower

h = Hours of usage at load factor (l)

After the work output has been determined, emissions are simply the product of the work output and the emission factor. An approximate load factor for a line-haul locomotive (road service) is 0.4; a typical switch engine load factor is approximately 0.06.[1]

References for Section 3.2.2

1. Hare, C.T. and K.J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part 1. Locomotive Diesel Engines and Marine Counterparts. Final Report. Southwest Research Institute. San Antonio, Texas. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHA 70-108. October 1972.

2. Young, T.C. Unpublished Data from the Engine Manufacturers Association. Chicago, Ill. May 1970.

3. Hanley, G.P. Exhaust Emission Information on Electro-Motive Railroad Locomotives and Diesel Engines. General Motors Corp. Warren, Mich. October 1971.

3.2.3 Inboard-Powered Vessels

Revised by David S. Kircher

3.2.3.1 General – Vessels classified on the basis of use will generally fall into one of three categories: commercial, pleasure, or military. Although usage and population data on vessels are, as a rule, relatively scarce, information on commercial and military vessels is more readily available than data on pleasure craft. Information on military vessels is available in several study reports,[1-5] but data on pleasure craft are limited to sales-related facts and figures.[6-10]

Commercial vessel population and usage data have been further subdivided by a number of industrial and governmental researchers into waterway classifications[11-16] (for example, Great Lakes vessels, river vessels, and coastal vessels). The vessels operating in each of these waterway classes have similar characteristics such as size, weight, speed, commodities transported, engine design (external or internal combustion), fuel used, and distance traveled. The wide variation between classes, however, necessitates the separate assessment of each of the waterway classes with respect to air pollution.

Information on military vessels is available from both the U.S. Navy and the U.S. Coast Guard as a result of studies completed recently. The U.S. Navy has released several reports that summarize its air pollution assessment work.[1-5] Emission data have been collected in addition to vessel population and usage information. Extensive study of the air pollutant emissions from U.S. Coast Guard watercraft has been completed by the U.S. Department of Transportation. The results of this study are summarized in two reports.[1,2] The first report takes an in-depth look at population/usage of Coast Guard vessels. The second report, dealing with emission test results, forms the basis for the emission factors presented in this section for Coast Guard vessels as well as for non-military diesel vessels.

Although a large portion of the pleasure craft in the U.S. are powered by gasoline outboard motors (see section 3.2.4 of this document), there are numerous larger pleasure craft that use inboard power either with or without "out-drive" (an outboard-like lower unit). Vessels falling into the inboard pleasure craft category utilize either Otto cycle (gasoline) or diesel cycle internal combustion engines. Engine horsepower varies appreciably from the small "auxiliary" engine used in sailboats to the larger diesels used in yachts.

3.2.3.2 Emissions

Commercial vessels. Commercial vessels may emit air pollutants under two major modes of operation: underway and at dockside (auxiliary power).

Emissions underway are influenced by a great variety of factors including power source (steam or diesel), engine size (in kilowatts or horsepower), fuel used (coal, residual oil, or diesel oil), and operating speed and load. Commercial vessels operating within or near the geographic boundaries of the United States fall into one of the three categories of use discussed above (Great Lakes, rivers, coastline). Tables 3.2.3-1 and 3.2.3-2 contain emission information on commercial vessels falling into these three categories. Table 3.2.3-3 presents emission factors for diesel marine engines at various operating modes on the basis of horsepower. These data are applicable to any vessel having a similar size engine, not just to commercial vessels.

Unless a ship receives auxiliary steam from dockside facilities, goes immediately into drydock, or is out of operation after arrival in port, she continues her emissions at dockside. Power must be made available for the ship's lighting, heating, pumps, refrigeration, ventilation, etc. A few steam ships use auxiliary engines (diesel) to supply power, but they generally operate one or more main boilers under reduced draft and lowered fuel rates–a very inefficient process. Motorships (ships powered by internal combustion engines) normally use diesel-powered generators to furnish auxiliary power.[17] Emissions from these diesel-powered generators may also be a source of underway emissions if they are used away from port. Emissions from auxiliary power systems, in terms of the

Table 3.2.3-1. AVERAGE EMISSION FACTORS FOR COMMERCIAL MOTORSHIPS BY WATERWAY CLASSIFICATION
EMISSION FACTOR RATING: C

Emissions[a]	Class[c]		
	River	Great Lakes	Coastal
Sulfur oxides[b] (SO_x as SO_2)			
kg/10^3 liter	3.2	3.2	3.2
lb/10^3 gal	27	27	27
Carbon monoxide			
kg/10^3 liter	12	13	13
lb/10^3 gal	100	110	110
Hydrocarbons			
kg/10^3 liter	6.0	7.0	6.0
lb/10^3 gal	50	59	50
Nitrogen oxides (NO_x as NO_2)			
kg/10^3 liter	33	31	32
lb/10^3 gal	280	260	270

[a] Expressed as function of fuel consumed. Based on emission data from Reference 2 and population/usage data from References 11 through 16.

[b] Calculated, not measured. Based on 0.20 percent sulfur content fuel and density of 0.854 kg/liter (7.12 lb/gal) from Reference 17.

[c] Very approximate particulate emission factors from Reference 2 are 470 g/hr (1.04 lb/hr). The reference does not contain sufficient information to calculate fuel-based factors.

quantity of fuel consumed, are presented in Table 3.2.3-4. In some instances, fuel quantities used may not be available, so calculation of emissions based on kilowatt hours (kWh) produced may be necessary. For operating loads in excess of zero percent, the mass emissions (e_l) in kilograms per hour (pounds per hour) are given by:

$$e_l = kle_f \qquad (1)$$

where: k = a constant that relates fuel consumption to kilowatt hours,[2]

that is, 3.63×10^{-4} 1000 liters fuel/kWh

or

9.59×10^{-5} 1000 gal fuel/kWh

l = the load, kW

e_f = the fuel-specific emission factor from Table 3.2.3-4, kg/10^3 liter (lb/10^3 gal)

Table 3.2.3-2. EMISSION FACTORS FOR COMMERCIAL STEAMSHIPS—ALL GEOGRAPHIC AREAS
EMISSION FACTOR RATING: D

Pollutant	Fuel and operating mode[a]											
	Residual oil[b]						Distillate oil[b]					
	Hoteling		Cruise		Full		Hoteling		Cruise		Full	
	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal
Particulate[c]	1.20[d]	10.0[d]	2.40	20.0	6.78	56.5	1.8	15	1.78	15	1.78	15
Sulfur oxides (SO_x as SO_2)[e]	19.1S	159S	19.1S	159S	19.1S	159S	17.0S	142S	17.0S	142S	17.0S	142S
Carbon monoxide[c]	Neg[d]	Neg[d]	0.414	3.45	0.872	7.27	0.5	4	0.5	4	0.5	4
Hydrocarbons[c]	0.38[d]	3.2[d]	0.082	0.682	0.206	1.72	0.4	3	0.4	3	0.4	3
Nitrogen oxides (NO_x as NO_2)	4.37	36.4	6.70	55.8	7.63	63.6	2.66	22.2	2.63	21.9	5.34	44.5

[a] The operating modes are based on the percentage of maximum available power: [illegible] "cruise" is an intermediate power [illegible]

[b] [illegible] "Residual" [illegible] "Distillate" [illegible]

[c] [illegible]

[d] [illegible]

[e] [illegible] these theoretical factors. "S" is fuel sulfur content in percent.

Table 3.2.3-3. DIESEL VESSEL EMISSION FACTORS BY OPERATING MODE[a]
EMISSION FACTOR RATING: C

Horsepower	Mode	Emissions[b]					
		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)	
		lb/10³ gal	kg/10³ liter	lb/10³ gal	kg/10³ liter	lb/10³ gal	kg/10³ liter
200	Idle	210.3	25.2	391.2	46.9	6.4	0.8
	Slow	145.4	17.4	103.2	12.4	207.8	25.0
	Cruise	126.3	15.1	170.2	20.4	422.9	50.7
	Full	142.1	17.0	60.0	7.2	255.0	30.6
300	Slow	59.0	7.1	56.7	6.8	337.5	40.4
	Cruise	47.3	5.7	51.1	6.1	389.3	46.7
	Full	58.5	7.0	21.0	2.5	275.1	33.0
500	Idle	282.5	33.8	118.1	14.1	99.4	11.9
	Cruise	99.7	11.9	44.5	5.3	338.6	40.6
	Full	84.2	10.1	22.8	2.7	269.2	32.3
600	Idle	171.7	20.6	68.0	8.2	307.1	36.8
	Slow	50.8	6.1	16.6	2.0	251.5	30.1
	Cruise	77.6	9.3	24.1	2.9	349.2	41.8
700	Idle	293.2	35.1	95.8	11.5	246.0	29.5
	Cruise	36.0	4.3	8.8	1.1	452.8	54.2
800	Idle	223.7	26.8	249.1	29.8	107.5	12.9
	2/3	62.2	7.5	16.8	2.0	167.2	20.0
	Cruise	80.9	9.7	17.1	2.1	360.0	43.1
1550	Idle	12.2	1.5	–	–	39.9	4.8
	Cruise	3.3	0.4	0.84	0.1	36.2	4.3
	Full	7.0	0.8	1.64	0.2	37.4	4.5
1800	Slow	122.4	14.7	–	–	371.3	44.5
	Cruise	44.6	5.3	–	–	623.1	74.6
	Full	237.7	28.5	16.6	2.0	472.0	5.7
2500	Slow	59.8	7.2	22.6	2.7	419.6	50.3
	2/3	126.5	15.2	14.7	1.8	326.2	39.1
	Cruise	78.3	9.4	16.8	2.0	391.7	46.9
	Full	95.9	11.5	21.3	2.6	399.6	47.9
3600	Slow	148.5	17.8	60.0	7.2	367.0	44.0
	2/3	28.1	3.4	25.4	3.0	358.6	43.0
	Cruise	41.4	5.0	32.8	4.0	339.6	40.7
	Full	62.4	7.5	29.5	3.5	307.0	36.8

[a] Reference 2.
[b] Particulate and sulfur oxides data are not available.

Table 3.2.3-5. AVERAGE EMISSION FACTORS FOR DIESEL POWERED ELECTRICAL GENERATORS IN VESSELS[a]
EMISSION FACTOR RATING: C

Rated output,[b] kW	Load,[c] % rated output	Emissions							
		Sulfur oxides (SO_x as SO_2)[d]		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)	
		$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter
20	0	27	3.2	150	18.0	263	31.5	434	52.0
	25	27	3.2	79.7	9.55	204	24.4	444	53.2
	50	27	3.2	53.4	6.40	144	17.3	477	57.2
	75	27	3.2	28.5	3.42	84.7	10.2	495	59.3
40	0	27	3.2	153	18.3	584	70.0	214	25.6
	25	27	3.2	89.0	10.7	370	44.3	219	26.2
	50	27	3.2	67.6	8.10	285	34.2	226	27.1
	75	27	3.2	64.1	7.68	231	27.7	233	27.9
200	0	27	3.2	134	16.1	135	16.2	142	17.0
	25	27	3.2	97.9	11.7	33.5	4.01	141	16.9
	50	27	3.2	62.3	7.47	17.8	2.13	140	16.8
	75	27	3.2	26.7	3.20	17.5	2.10	137	16.4
500	0	27	3.2	58.4	7.00	209	25.0	153	18.3
	25	27	3.2	53.4	6.40	109	13.0	222	26.6
	50	27	3.2	48.1	5.76	81.9	9.8	293	35.1
	75	27	3.2	43.7	5.24	59.1	7.08	364	43.6

[a] Reference 9.

[b] Maximum rated output of the diesel-powered generator.

[c] Generator electrical output (for example, a 20 kW generator at 50 percent load equals 10 kW output).

[d] Calculated, not measured, based on 0.20 percent fuel sulfur content and density of 0.854 kg/liter (7.12 lb/gal) from Reference 11.

At zero load conditions, mass emission rates (e_i) may be approximated in terms of kg/hr (lb/hr) using the following relationship:

$$e_i = k l_{rated} e_f \qquad (3)$$

where: k = a constant that relates rated output and fuel consumption,

that is, 6.93×10^{-5} 1000 liters fuel/kW

or

1.83×10^{-5} 10^3 gal fuel/kW

l_{rated} = the rated output, kW

e_f = the fuel-specific emission factor from Table 3.2.3-4, $kg/10^3$ liter ($lb/10^3$ gal)

Pleasure craft. Many of the engine designs used in inboard pleasure craft are also used either in military vessels (diesel) or in highway vehicles (gasoline). Out of a total of 700,000 inboard pleasure craft registered in the United States in 1973, nearly 300,000 were inboard/outdrive. According to sales data, 60 to 70 percent of these inboard/outdrive craft used gasoline-powered automotive engines rated at more than 130 horsepower.[8] The remaining 400,000 pleasure craft used conventional inboard drives that were powered by a variety of powerplants, both gasoline and diesel. Because emission data are not available for pleasure craft, Coast Guard and automotive data[2,7,9] are used to characterize emission factors for this class of vessels in Table 3.2.3-5.

Military vessels. Military vessels are powered by a wide variety of both diesel and steam power plants. Many of the emission data used in this section are the result of emission testing programs conducted by the U.S. Navy and the U.S. Coast Guard.[1,3,12] A separate table containing data on military vessels is not provided here, but the included tables should be sufficient to calculate approximate military vessel emissions.

TABLE 3.2.3-5. AVERAGE EMISSION FACTORS FOR INBOARD PLEASURE CRAFT[a]

EMISSION FACTOR RATING: D

	Based on fuel consumption				Based on operating time			
	Diesel engine[b]		Gasoline engine[c]		Diesel engine[b]		Gasoline engine[c]	
Pollutant	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/hr	lb/hr	kg/hr	lb/hr
Sulfur oxides[d] (SO_x as SO_2)	3.2	27	0.77	6.4	-	-	0.008	0.019
Carbon monoxide	17	140	149	1240	-	-	1.69	3.73
Hydrocarbons	22	180	10.3	86	-	-	0.117	0.258
Nitrogen oxides (NO_x as NO_2)	41	340	16.7	131	-	-	0.179	0.394

[a] Average emission factors are based on the duty cycle developed for large outboards (≥ 48 kilowatts or ≥ 65 horsepower) from Reference 7. The above factors take into account the impact of water scrubbing of underwater gasoline engine exhaust, also from Reference 7. All values given are for single engine craft and must be modified for multiple engine vessels.

[b] Based on tests of diesel engines in Coast Guard vessels, Reference 2.

[c] Based on tests of automotive engines, Reference 10. Fuel consumption of 11.4 liter/hr (3 gal/hr) assumed. The resulting factors are only rough estimates.

[d] Based on fuel sulfur content of 0.20 percent for diesel fuel and 0.043 percent for gasoline from References 7 and 11. Calculated using fuel density of 0.740 kg/liter (6.17 lb/gal) for gasoline and 0.854 kg/liter (7.12 lb/gal) for diesel fuel.

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3.2.4 Outboard-Powered Vessels

by David S. Kircher

3.2.4.1 General – Most of the approximately 7 million outboard motors in use in the United States are 2-stroke engines with an average available horsepower of about 25. Because of the predominately leisure-time use of outboard motors, emissions related to their operation occur primarily during nonworking hours, in rural areas, and during the three summer months. Nearly 40 percent of the outboards are operated in the states of New York, Texas, Florida, Michigan, California, and Minnesota. This distribution results in the concentration of a large portion of total nationwide outboard emissions in these states.[1]

3.2.4.2 Emissions – Because the vast majority of outboards have underwater exhaust, emission measurement is very difficult. The values presented in Table 3.2.4-1 are the approximate atmospheric emissions from outboards. These data are based on tests of four outboard motors ranging from 4 to 65 horsepower.[1] The emission results from these motors are a composite based on the nationwide breakdown of outboards by horsepower. Emission factors are presented two ways in this section: in terms of fuel use and in terms of work output (horsepower hour). The selection of the factor used depends on the source inventory data available. Work output factors are used when the number of outboards in use is available. Fuel-specific emission factors are used when fuel consumption data are obtainable.

Table 3.2.4-1. AVERAGE EMISSION FACTORS FOR OUTBOARD MOTORS[a]
EMISSION FACTOR RATING: B

	Based on fuel consumption		Based on work output[c]	
Pollutant[b]	lb/10³ gal	kg/10³ liter	g/hphr	g/metric hphr
Sulfur oxides[d] (SO_x as SO_2)	6.4	0.77	0.49	0.49
Carbon monoxide	3300	400	250	250
Hydrocarbons[e]	1100	130	85	85
Nitrogen oxides (NO_x as NO_2)	6.6	0.79	0.50	0.50

[a] Reference 1. Data in this table are emissions to the atmosphere. A portion of the exhaust remains behind in the water.

[b] Particulate emission factors are not available because of the problems involved with measurement from an underwater exhaust system but are considered negligible.

[c] Horsepower hours are calculated by multiplying the average power produced during the hours of usage by the population of outboards in a given area. In the absence of data specific to a given geographic area, the hphr value can be estimated using average nationwide values from Reference 1. Reference 1 reports the average power produced (not the available power) as 9.1 hp and the average annual usage per engine as 50 hours. Thus, hphr = (number of outboards) (9.1 hp) (50 hours/outboard-year). Metric hphr = 0.9863 hphr.

[d] Based on fuel sulfur content of 0.043 percent from Reference 2 and on a density of 6.17 lb/gal.

[e] Includes exhaust hydrocarbons only. No crankcase emissions occur because the majority of outboards are 2-stroke engines that use crankcase induction. Evaporative emissions are limited by the widespread use of unvented tanks.

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3.2.5 Small, General Utility Engines

Revised by Charles C. Masser

3.2.5.1 General. This category of engines comprises small 2-stroke and 4-stroke, air-cooled, gasoline-powered motors. Examples of the uses of these engines are: lawnmowers, small electric generators, compressors, pumps, minibikes, snowthrowers, and garden tractors. This category does *not* include motorcycles, outboard motors, chain saws, and snowmobiles, which are either included in other parts of this chapter or are not included because of the lack of emission data.

Approximately 89 percent of the more than 44 million engines of this category in service in the United States are used in lawn and garden applications.[1]

3.2.5.2 Emissions. Emissions from these engines are reported in Table 3.2.5-1. For the purpose of emission estimation, engines in this category have been divided into lawn and garden (2-stroke), lawn and garden (4-stroke), and miscellaneous (4-stroke). Emission factors are presented in terms of horsepower hours, annual usage, and fuel consumption.

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Table 3.2.5-1. EMISSION FACTORS FOR SMALL, GENERAL UTILITY ENGINES[a,b]
EMISSION FACTOR RATING: B

Engine	Sulfur oxides[c] (SO_x as SO_2)	Particulate	Carbon monoxide	Hydrocarbons		Nitrogen oxides (NO_x as NO_2)	Aldehydes (HCHO)
				Exhaust	Evaporative[d]		
2-Stroke, lawn and garden							
g/hphr	0.54	7.1	486	214	–	1.58	2.04
g/metric hphr	0.54	7.1	486	214	–	1.58	2.04
g/gal of fuel	1.80	23.6	1,618	713	–	5.26	6.79
g/unit year	38	470	33,100	14,700	113	108	140
4-Stroke, lawn and garden							
g/hphr	0.37	0.44	279	23.2	–	3.17	0.49
g/metric hphr	0.37	0.44	279	23.2	–	3.17	0.49
g/gal of fuel	2.37	2.82	1,790	149	–	20.3	3.14
g/unit year	26	31	19,100	1,590	113	217	34
4-Stroke miscellaneous							
g/hphr	0.39	0.44	250	15.2	–	4.97	0.47
g/metric hphr	0.39	0.44	250	15.2	–	4.97	0.47
g/gal of fuel	2.45	2.77	1,571	95.5	–	31.2	2.95
g/unit year	30	34	19,300	1,170	200	384	36

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[a] Reference 2.

[b] Values for g/unit-year were calculated assuming an annual usage of 50 hours and a 40 percent load factor. Factors for g/hphr can be used in instances where annual usages, load factors, and rated horsepower are known. Horsepower hours are the product of the usage in hours, the load factor, and the rated horsepower.

[c] Values calculated, not measured, based on the use of 0.043 percent sulfur content fuel.

[d] Values calculated from annual fuel consumption. Evaporative losses from storage and filling operations are not included (see Chapter 4).

3.2.6 Agricultural Equipment

by David S. Kircher

3.2.6.1 General – Farm equipment can be separated into two major categories: wheeled tractors and other farm machinery. In 1972, the wheeled tractor population on farms consisted of 4.5 million units with an average power of approximately 34 kilowatts (45 horsepower). Approximately 30 percent of the total population of these tractors is powered by diesel engines. The average diesel tractor is more powerful than the average gasoline tractor, that is, 52 kW (70 hp) versus 27 kW (36 hp).[1] A considerable amount of population and usage data is available for farm tractors. For example, the Census of Agriculture reports the number of tractors in use for each county in the U.S.[2] Few data are available on the usage and numbers of non-tractor farm equipment, however. Self-propelled combines, forage harvesters, irrigation pumps, and auxiliary engines on pull-type combines and balers are examples of non-tractor agricultural uses of internal combustion engines. Table 3.2.6-1 presents data on this equipment for the U.S.

3.2.6.2 Emissions – Emission factors for wheeled tractors and other farm machinery are presented in Table 3.2.6-2. Estimating emissions from the time-based emission factors (grams per hour [g/hr] and pounds per hour [lb/hr]) requires an average usage value in hours. An approximate figure of 550 hours per year may be used or, on the basis of power, the relationship, usage in hours = 450 + 5.24 (kW - 37.2) or usage in hours = 450 + 3.89 (hp - 50) may be employed.[1]

The best emissions estimates result from the use of "brake specific" emission factors (g/kWh or g/hphr). Emissions are the product of the brake specific emission factor, the usage in hours, the power available, and the load factor (power used divided by power available). Emissions are also reported in terms of fuel consumed.

Table 3.2.6-1. SERVICE CHARACTERISTICS OF FARM EQUIPMENT (OTHER THAN TRACTORS)[a]

Machine	Units in service, x 10^3	Typical size	Typical power kW	Typical power hp	Percent gasoline	Percent diesel
Combine, self-propelled	434	4.3 m (14 ft)	82	110	50	50
Combine, pull-type	289	2.4 m (8 ft)	19	26	100	0
Corn pickers and picker-shellers	687	2-row	–[b]	–	–	–
Pick-up balers	665	5400 kg/hr (6 ton/hr)	30	40	100	0
Forage harvesters	295	3.7 m (12 ft) or 3-row	104	140	0	100
Miscellaneous	1205	–	22	30	50	50

[a] Reference 1.

[b] Unpowered.

Table 3.2.6-2. EMISSION FACTORS FOR WHEELED FARM TRACTORS AND NON-TRACTOR AGRICULTURAL EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Diesel farm tractor	Gasoline farm tractor	Diesel farm equipment (non-tractor)	Gasoline farm equipment (non-tractor)
Carbon monoxide				
g/hr	161	3,380	95.2	4,360
lb/hr	0.355	7.46	0.210	9.62
g/kWh	4.48	192	6.41	292
g/hphr	3.34	143	4.78	218
kg/10^3 liter	14.3	391	16.7	492
lb/10^3 gal	119	3,260	139	4,100
Exhaust hydrocarbons				
g/hr	77.8	128	38.6	143
lb/hr	0.172	0.282	0.085	0.315
g/kWh	2.28	7.36	2.25	9.63
g/hphr	1.70	5.49	1.68	7.18
kg/10^3 liter	7.28	15.0	6.85	16.2
lb/10^3 gal	60.7	125	57.1	135
Crankcase hydrocarbons[b]				
g/hr	–	26.0	–	28.6
lb/hr	–	0.057	–	0.063
g/kWh	–	1.47	–	1.93
g/hphr	–	1.10	–	1.44
kg/10^3 liter	–	3.01	–	3.25
lb/10^3 gal	–	25.1	–	27.1
Evaporative hydrocarbons[b]				
g/unit-year	–	15,600	–	1,600
lb/unit-year	–	34.4	–	3.53
Nitrogen oxides (NO_x as NO_2)				
g/hr	452	157	210	105
lb/hr	0.996	0.346	0.463	0.231
g/kWh	12.6	8.88	12.11	7.03
g/hphr	9.39	6.62	9.03	5.24
kg/10^3 liter	40.2	18.1	36.5	11.8
lb/10^3 gal	335	151	307	98.5
Aldehydes (RCHO as HCHO)				
g/hr	16.3	7.07	7.23	4.76
lb/hr	0.036	0.016	0.016	0.010
g/kWh	0.456	0.402	0.402	0.295
g/hphr	0.340	0.300	0.30	0.220
kg/10^3 liter	1.45	0.821	1.22	0.497
lb/10^3 gal	12.1	6.84	10.2	4.14
Sulfur oxides[c] (SO_x as SO_2)				
g/hr	42.2	5.56	21.7	6.31
lb/hr	0.093	0.012	0.048	0.014

Table 3.2.6-2. (continued). EMISSION FACTORS FOR WHEELED FARM TRACTORS AND NON-TRACTOR AGRICULTURAL EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Diesel farm tractor	Gasoline farm tractor	Diesel farm equipment (non-tractor)	Gasoline farm equipment (non-tractor)
g/kWh	1.17	0.312	1.23	0.377
g/hphr	0.874	0.233	0.918	0.281
kg/10^3 liter	3.74	0.637	3.73	0.634
lb/10^3 gal	31.2	5.31	31.1	5.28
Particulate				
g/hr	61.8	8.33	34.9	7.94
lb/hr	0.136	0.018	0.077	0.017
g/kWh	1.72	0.471	2.02	0.489
g/hphr	1.28	0.361	1.51	0.365
kg/10^3 liter	5.48	0.960	6.16	0.823
lb/10^3 gal	45.7	8.00	51.3	6.86

[a] Reference 1.

[b] Crankcase and evaporative emissions from diesel engines are considered negligible.

[c] Not measured. Calculated from fuel sulfur content of 0.043 percent and 0.22 percent for gasoline-powered and diesel-powered equipment, respectively.

References for Section 3.2.6

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 5: Heavy-Duty Farm, Construction and Industrial Engines. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. August 1973. 97 p.

2. County Farm Reports. U.S. Census of Agriculture. U.S. Department of Agriculture. Washington, D.C.

3.2.7 Heavy-Duty Construction Equipment

by David S. Kircher

3.2.7.1 General – Because few sales, population, or usage data are available for construction equipment, a number of assumptions were necessary in formulating the emission factors presented in this section.[1] The useful life of construction equipment is fairly short because of the frequent and severe usage it must endure. The annual usage of the various categories of equipment considered here ranges from 740 hours (wheeled tractors and rollers) to 2000 hours (scrapers and off-highway trucks). This high level of use results in average vehicle lifetimes of only 6 to 16 years. The equipment categories in this section include: tracklaying tractors, tracklaying shovel loaders, motor graders, scrapers, off-highway trucks, wheeled loaders, wheeled tractors, rollers, wheeled dozers, and miscellaneous machines. The latter category contains a vast array of less numerous mobile and semi-mobile machines used in construction, such as, belt loaders, cranes, pumps, mixers, and generators. With the exception of rollers, the majority of the equipment within each category is diesel-powered.

3.2.7.2 Emissions – Emission factors for heavy-duty construction equipment are reported in Table 3.2.7-1 for diesel engines and in Table 3.2.7-2 for gasoline engines. The factors are reported in three different forms: on the basis of running time, fuel consumed, and power consumed. In order to estimate emissions from time-based emission factors, annual equipment usage in hours must be estimated. The following estimates of use for the equipment listed in the tables should permit reasonable emission calculations.

Category	Annual operation, hours/year
Tracklaying tractors	1050
Tracklaying shovel loaders	1100
Motor graders	830
Scrapers	2000
Off-highway trucks	2000
Wheeled loaders	1140
Wheeled tractors	740
Rollers	740
Wheeled dozers	2000
Miscellaneous	1000

The best method for calculating emissions, however, is on the basis of "brake specific" emission factors (g/kWh or g/hphr). Emissions are calculated by taking the product of the brake specific emission factor, the usage in hours, the power available (that is, rated power), and the load factor (the power actually used divided by the power available).

References for Section 3.2.7

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines – Final Report. Part 5: Heavy-Duty Farm, Construction, and Industrial Engines. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. October 1973. 105 p.

2. Hare, C. T. Letter to C. C. Masser of Environmental Protection Agency, Research Triangle Park, N.C., concerning fuel-based emission rates for farm, construction, and industrial engines. San Antonio, Tex. January 14, 1974. 4 p.

Table 3.2.7-1. EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Tracklaying tractor	Wheeled tractor	Wheeled dozer	Scraper	Motor grader
Carbon monoxide					
g/hr	175.	973.	335.	660.	97.7
lb/hr	0.386	2.15	0.739	1.46	0.215
g/kWh	3.21	5.90	2.45	3.81	2.94
g/hphr	2.39	4.40	1.83	2.84	2.19
kg/10^3 liter	10.5	19.3	7.90	11.8	9.35
lb/10^3 gal	87.5	161.	65.9	98.3	78.0
Exhaust hydrocarbons					
g/hr	50.1	67.2	106.	284.	24.7
lb/hr	0.110	0.148	0.234	0.626	0.054
g/kWh	0.919	1.86	0.772	1.64	0.656
g/hphr	0.685	1.39	0.576	1.22	0.489
kg/10^3 liter	3.01	6.10	2.48	5.06	2.09
lb/10^3 gal	25.1	50.9	20.7	42.2	17.4
Nitrogen oxides (NO_x as NO_2)					
g/hr	665.	451.	2290.	2820.	478.
lb/hr	1.47	0.994	5.05	6.22	1.05
g/kWh	12.2	12.5	16.8	16.2	14.1
g/hphr	9.08	9.35	12.5	12.1	10.5
kg/10^3 liter	39.9	41.0	53.9	50.2	44.9
lb/10^3 gal	332.	342.	450.	419.	374.
Aldehydes (RCHO as HCHO)					
g/hr	12.4	13.5	29.5	65.	5.54
lb/hr	0.027	0.030	0.065	0.143	0.012
g/kWh	0.228	0.378	0.215	0.375	0.162
g/hphr	0.170	0.282	0.160	0.280	0.121
kg/10^3 liter	0.745	1.23	0.690	1.16	0.517
lb/10^3 gal	6.22	10.3	5.76	9.69	4.31
Sulfur oxides (SO_x as SO_2)					
g/hr	62.3	40.9	158.	210.	39.0
lb/hr	0.137	0.090	0.348	0.463	0.086
g/kWh	1.14	1.14	1.16	1.21	1.17
g/hphr	0.851	0.851	0.867	0.901	0.874
kg/10^3 liter	3.73	3.73	3.74	3.74	3.73
lb/10^3 gal	31.1	31.1	31.2	31.2	31.1
Particulate					
g/hr	50.7	61.5	75.	184.	27.7
lb/hr	0.112	0.136	0.165	0.406	0.061
g/kWh	0.928	1.70	0.551	1.06	0.838
g/hphr	0.692	1.27	0.411	0.789	0.625
kg/10^3 liter	3.03	5.57	1.77	3.27	2.68
lb/10^3 gal	25.3	46.5	14.8	27.3	22.2

[a] References 1 and 2.

Table 3.2.7-1 (continued). EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Wheeled loader	Tracklaying loader	Off-Highway truck	Roller	Miscellaneous
Carbon monoxide					
g/hr	251.	72.5	610.	83.5	188.
lb/hr	0.553	0.160	1.34	0.184	0.414
g/kWh	3.51	2.41	3.51	4.89	3.78
g/hphr	2.62	1.80	2.62	3.65	2.82
kg/10^3 liter	11.4	7.90	11.0	13.7	11.3
lb/10^3 gal	95.4	65.9	92.2	114.	94.2
Exhaust hydrocarbons					
g/hr	84.7	14.5	106.	26.7	71.4
lb/hr	0.187	0.032	0.437	0.059	0.157
g/kWh	1.19	0.485	1.14	1.05	1.39
g/hphr	0.888	0.362	0.853	0.781	1.04
kg/10^3 liter	3.87	1.58	3.60	2.91	4.16
lb/10^3 gal	32.3	13.2	30.0	24.3	34.7
Nitrogen oxides (NO_x as NO_2)					
g/hr	1090.	265.	3460.	474.	1030.
lb/hr	2.40	0.584	7.63	1.04	2.27
g/kWh	15.0	8.80	20.0	21.1	19.8
g/hphr	11.2	6.56	14.9	15.7	14.8
kg/10^3 liter	48.9	28.8	62.8	58.5	59.2
lb/10^3 gal	408.	240.	524.	488.	494.
Aldehydes (RCHO as HCHO)					
g/hr	18.8	4.00	51.0	7.13	13.9
lb/hr	0.041	0.009	0.112	0.016	0.031
g/kWh	0.264	0.134	0.295	0.263	0.272
g/hphr	0.197	0.100	0.220	0.196	0.203
kg/10^3 liter	0.859	0.439	0.928	0.731	0.813
lb/10^3 gal	7.17	3.66	7.74	6.10	6.78
Sulfur oxides (SO_x as SO_2)					
g/hr	82.5	34.4	206.	30.5	64.7
lb/hr	0.182	0.076	0.454	0.067	0.143
g/kWh	1.15	1.14	1.19	1.34	1.25
g/hphr	0.857	0.853	0.887	1.00	0.932
kg/10^3 liter	3.74	3.74	3.74	3.73	3.73
lb/10^3 gal	31.2	31.2	31.2	31.1	31.1
Particulate					
g/hr	77.9	26.4	116.	22.7	63.2
lb/hr	0.172	0.058	0.256	0.050	0.139
g/kWh	1.08	0.878	0.673	1.04	1.21
g/hphr	0.805	0.655	0.502	0.778	0.902
kg/10^3 liter	3.51	2.88	2.12	2.90	3.61
lb/10^3 gal	29.3	24.0	17.7	24.2	30.1

[a] References 1 and 2.

Table 3.2.7-2. EMISSION FACTORS FOR HEAVY DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Wheeled tractor	Motor grader	Wheeled loader	Roller	Miscellaneous
Carbon monoxide					
g/hr	4320.	5490.	7060.	6080.	7720.
lb/hr	9.52	12.1	15.6	13.4	17.0
g/kWh	190.	251.	219.	271.	266.
g/hphr	142.	187.	163.	202.	198.
kg/10^3 liter	389.	469.	435.	460.	475.
lb/10^3 gal	3250.	3910.	3630.	3840.	3960.
Exhaust hydrocarbons					
g/hr	164.	186.	241.	277.	254.
lb/hr	0.362	0.410	0.531	0.611	0.560
g/kWh	7.16	8.48	7.46	12.40	8.70
g/hphr	5.34	6.32	5.56	9.25	6.49
kg/10^3 liter	14.6	15.8	14.9	21.1	15.6
lb/10^3 gal	122.	132.	124.	176.	130.
Evaporative hydrocarbons[b]					
g/hr	30.9	30.0	29.7	28.2	25.4
lb/hr	0.0681	0.0661	0.0655	0.0622	0.0560
Crankcase hydrocarbons[b]					
g/hr	32.6	37.1	48.2	55.5	50.7
lb/hr	0.0719	0.0818	0.106	0.122	0.112
Nitrogen oxides (NO_x as NO_2)					
g/hr	195.	145.	235.	164.	187.
lb/hr	0.430	0.320	0.518	0.362	0.412
g/kWh	8.54	6.57	7.27	7.08	6.42
g/hphr	6.37	4.90	5.42	5.28	4.79
kg/10^3 liter	17.5	12.2	14.5	12.0	11.5
lb/10^3 gal	146.	102.	121.	100.	95.8
Aldehydes (RCHO as HCHO)					
g/hr	7.97	8.80	9.65	7.57	9.00
lb/hr	0.0176	0.0194	0.0213	0.0167	0.0198
g/kWh	0.341	0.386	0.298	0.343	0.298
g/hphr	0.254	0.288	0.222	0.256	0.222
kg/10^3 liter	0.687	0.721	0.593	0.582	0.532
lb/10^3 gal	5.73	6.02	4.95	4.86	4.44
Sulfur oxides (SO_x as SO_2)					
g/hr	7.03	7.59	10.6	8.38	10.6
lb/hr	0.0155	0.0167	0.0234	0.0185	0.0234
g/kWh	0.304	0.341	0.319	0.373	0.354
g/hphr	0.227	0.254	0.238	0.278	0.264
kg/10^3 liter	0.623	0.636	0.636	0.633	0.633
lb/10^3 gal	5.20	5.31	5.31	5.28	5.28

Table 3.2.7-2. (continued). EMISSION FACTORS FOR HEAVY-DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Wheeled tractor	Motor grader	Wheeled loader	Roller	Miscel-laneous
Particulate					
g/hr	10.9	9.40	13.5	11.8	11.7
lb/hr	0.0240	0.0207	0.0298	0.0260	0.0258
g/kWh	0.484	0.440	0.421	0.527	0.406
g/hphr	0.361	0.328	0.314	0.393	0.303
kg/10^3 liter	0.991	0.822	0.839	0.895	0.726
lb/10^3 gal	8.27	6.86	7.00	7.47	6.06

[a] References 1 and 2.

[b] Evaporative and crankcase hydrocarbons based on operating time only (Reference 1).

3.2.8 Snowmobiles

by Charles C. Masser

3.2.8.1 General – In order to develop emission factors for snowmobiles, mass emission rates must be known, and operating cycles representative of usage in the field must be either known or assumed. Extending the applicability of data from tests of a few vehicles to the total snowmobile population requires additional information on the composition of the vehicle population by engine size and type. In addition, data on annual usage and total machine population are necessary when the effect of this source on national emission levels is estimated.

An accurate determination of the number of snowmobiles in use is quite easily obtained because most states require registration of the vehicles. The most notable features of these registration data are that almost 1.5 million sleds are operated in the United States, that more than 70 percent of the snowmobiles are registered in just four states (Michigan, Minnesota, Wisconsin, and New York), and that only about 12 percent of all snowmobiles are found in areas outside the northeast and northern midwest.

3.2.8.2 Emissions – Operating data on snowmobiles are somewhat limited, but enough are available so that an attempt can be made to construct a representative operating cycle. The required end products of this effort are time-based weighting factors for the speed/load conditions at which the test engines were operated; use of these factors will permit computation of "cycle composite" mass emissions, power consumption, fuel consumption, and specific pollutant emissions.

Emission factors for snowmobiles were obtained through an EPA-contracted study[1] in which a variety of snowmobile engines were tested to obtain exhaust emissions data. These emissions data along with annual usage data were used by the contractor to estimate emission factors and the nationwide emission impact of this pollutant source.

To arrive at average emission factors for snowmobiles, a reasonable estimate of average engine size was necessary. Weighting the size of the engine to the degree to which each engine is assumed to be representative of the total population of engines in service resulted in an estimated average displacement of 362 cubic centimeters (cm^3).

The speed/load conditions at which the test engines were operated represented, as closely as possible, the normal operation of snowmobiles in the field. Calculations using the fuel consumption data obtained during the tests and the previously approximated average displacement of 362 cm^3 resulted in an estimated average fuel consumption of 0.94 gal/hr.

To compute snowmobile emission factors on a gram per unit year basis, it is necessary to know not only the emission factors but also the annual operating time. Estimates of this usage are discussed in Reference 1. On a national basis, however, average snowmobile usage can be assumed to be 60 hours per year. Emission factors for snowmobiles are presented in Table 3.2.8-1.

References for Section 3.2.8

1. Hare, C. T. and K. J. Springer. Study of Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 7: Snowmobiles. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. April 1974.

Table 3.2.8-1. EMISSION FACTORS FOR SNOWMOBILES
EMISSION FACTOR RATING: B

Pollutant	Emissions			
	g/unit-year[a]	g/gal[b]	g/liter[b]	g/hr[b]
Carbon monoxide	58,700	1,040.	275.	978.
Hydrocarbons	37,800	670.	177.	630.
Nitrogen oxides	600	10.6	2.8	10.0
Sulfur oxides[c]	51	0.90	0.24	0.85
Solid particulate	1,670	29.7	7.85	27.9
Aldehydes (RCHO)	552	9.8	2.6	9.2

[a] Based on 60 hours of operation per year and 392 cm^3 displacement.

[b] Based on 392 cm^3 displacement and average fuel consumption of 0.94 gal/hr.

[c] Based on sulfur content of 0.043 percent by weight.

3.3 OFF-HIGHWAY, STATIONARY SOURCES

by David S. Kircher and
Charles C. Masser

In general, engines included in this category are internal combustion engines used in applications similar to those associated with external combustion sources (see Chapter 1). The major engines within this category are gas turbines and large, heavy-duty, general utility reciprocating engines. Emission data currently available for these engines are limited to gas turbines and natural-gas-fired, heavy-duty, general utility engines. Most stationary internal combustion engines are used to generate electric power, to pump gas or other fluids, or to compress air for pneumatic machinery.

3.3.1 Stationary Gas Turbines for Electric Utility Power Plants

3.3.1.1 General – Stationary gas turbines find application in electric power generators, in gas pipeline pump and compressor drives, and in various process industries. The majority of these engines are used in electrical generation for continuous, peaking, or standby power.[1] The primary fuels used are natural gas and No. 2 (distillate) fuel oil, although residual oil is used in a few applications.

3.3.1.2 Emissions – Data on gas turbines were gathered and summarized under an EPA contract.[2] The contractor found that several investigators had reported data on emissions from gas turbines used in electrical generation but that little agreement existed among the investigators regarding the terms in which the emissions were expressed. The efforts represented by this section include acquisition of the data and their conversion to uniform terms. Because many sets of measurements reported by the contractor were not complete, this conversion often involved assumptions on engine air flow or fuel flow rates (based on manufacturers' data). Another shortcoming of the available information was that relatively few data were obtained at loads below maximum rated (or base) load.

Available data on the population and usage of gas turbines in electric utility power plants are fairly extensive, and information from the various sources appears to be in substantial agreement. The source providing the most complete information is the Federal Power Commission, which requires major utilities (electric revenues of $1 million or more) to submit operating and financial data on an annual basis. Sawyer and Farmer[3] employed these data to develop statistics on the use of gas turbines for electric generation in 1971. Although their report involved only the major, publicly owned utilities (not the private or investor-owned companies), the statistics do appear to include about 87 percent of the gas turbine power used for electric generation in 1971.

Of the 253 generating stations listed by Sawyer and Farmer, 137 have more than one turbine-generator unit. From the available data, it is not possible to know how many hours *each* turbine was operated during 1971 for these multiple-turbine plants. The remaining 116 (single-turbine) units, however, were operated an average of 1196 hours during 1971 (or 13.7 percent of the time), and their average load factor (percent of rated load) during operation was 86.8 percent. This information alone is not adequate for determining a representative operating pattern for electric utility turbines, but it should help prevent serious errors.

Using 1196 hours of operation per year and 250 starts per year as normal, the resulting average operating day is about 4.8 hours long. One hour of no-load time per day would represent about 21 percent of operating time, which is considered somewhat excessive. For economy considerations, turbines are not run at off-design conditions any longer than necessary, so time spent at intermediate power points is probably minimal. The bulk of turbine operation must be at base or peak load to achieve the high load factor already mentioned.

If it is assumed that time spent at off-design conditions includes 15 percent at zero load and 2 percent each at 25 percent, 50 percent, and 75 percent load, then the percentages of operating time at rated load (100 percent) and peak load (assumed to be 125 percent of rated) can be calculated to produce an 86.8 percent load factor. These percentages turn out to be 19 percent at peak load and 60 percent at rated load; the postulated cycle based on this line of reasoning is summarized in Table 3.3.1-1.

Table 3.3.1-1. TYPICAL OPERATING CYCLE FOR ELECTRIC UTILITY TURBINES

Condition, % of rated power	Percent operating time spent at condition	Time at condition based on 4.8 hr day		Contribution to load factor at condition
		hours	minutes	
0	15	0.72	43	0.00 x 0.15 = 0.0
25	2	0.10	6	0.25 x 0.02 = 0.005
50	2	0.10	6	0.50 x 0.02 = 0.010
75	2	0.10	6	0.75 x 0.02 = 0.015
100 (base)	60	2.88	173	1.0 x 0.60 = 0.60
125 (peak)	19	0.91	55	1.25 x 0.19 = 0.238
		4.81	289	Load factor = 0.868

The operating cycle in Table 3.3.1-1 is used to compute emission factors, although it is only an estimate of actual operating patterns.

Table 3.3.1-2. COMPOSITE EMISSION FACTORS FOR 1971 POPULATION OF ELECTRIC UTILITY TURBINES EMISSION FACTOR RATING: B

Time basis	Nitrogen oxides	Hydrocarbons	Carbon Monoxide	Particulate	Sulfur oxides
Entire population					
lb/hr rated load[a]	8.84	0.79	2.18	0.52	0.33
kg/hr rated load	4.01	0.36	0.99	0.24	0.15
Gas fired only					
lb/hr rated load	7.81	0.79	2.18	0.27	0.098
kg/hr rated load	3.54	0.36	0.99	0.12	0.044
Oil fired only					
lb/hr rated load	9.60	0.79	2.18	0.71	0.50
kg/hr rated load	4.35	0.36	0.99	0.32	0.23
Fuel basis					
Gas fired only					
lb/10^6 ft^3 gas	413.	42.	115.	14.	940S[b]
kg/10^6 m^3 gas	6615.	673.	1842.	224.	15,000S
Oil fired only					
lb/10^3 gal oil	67.8	5.57	15.4	5.0	140S
kg/10^3 liter oil	8.13	0.668	1.85	0.60	16.8S

[a] Rated load expressed in megawatts.

[b] S is the percentage sulfur. Example: If the factor is 940 and the sulfur content is 0.01 percent, the sulfur oxides emitted would be 940 times 0.01, or 9.4 lb/10^6 ft^3 gas.

Table 3.3.1-2 is the resultant composite emission factors based on the operating cycle of Table 3.3.1-1 and the 1971 population of electric utility turbines.

Different values for time at base and peak loads are obtained by changing the total time at lower loads (0 through 75 percent) or by changing the distribution of time spent at lower loads. The cycle given in Table 3.3.1-1 seems reasonable, however, considering the fixed load factor and the economics of turbine operation. Note that the cycle determines *only* the importance of each load condition in computing composite emission factors for each type of turbine, *not* overall operating hours.

The top portion of Table 3.3.1-2 gives separate factors for gas-fired and oil-fired units, and the bottom portion gives fuel-based factors that can be used to estimate emission rates when overall fuel consumption data are available. Fuel-based emission factors on a mode basis would also be useful but present fuel consumption data are not adequate for this purpose.

References for Section 3.3.1

1. O'Keefe, W. and R. G. Schwieger. Prime Movers. Power. *115*(11): S22-S31. November 1971.

2. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 6: Gas Turbine Electric Utility Power Plants. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108, February 1974.

3. Sawyer, V. W. and R. C. Farmer. Gas Turbines in U.S. Electric Utilities. Gas Turbine International. January - April 1973.

3.3.2 Heavy-Duty, General Utility, Gaseous-Fueled Engines

3.3.2.1 General. – Engines in this category are used in the oil and gas industry for driving compressors in pipeline pressure boosting systems, in gas distribution systems, and in vapor recovery systems (at petroleum refineries). The engines burn either natural gas or refinery gas.

3.3.2.2 Emissions. – Emissions from heavy-duty, gaseous-fueled internal combustion engines are reported in Table 3.3.2-1. Test data were available for nitrogen oxides and hydrocarbons only; sulfur oxides are calculated from fuel sulfur content. Nitrogen oxides have been found to be extremely dependent on an engine's work output; hence, Figure 3.3.2-1 presents the relationship between nitrogen oxide emissions and horsepower.

Table 3.3.2-1. EMISSION FACTORS FOR HEAVY-DUTY, GENERAL-UTILITY, STATIONARY ENGINES USING GASEOUS FUELS

EMISSION FACTOR RATING: C

Pollutant	Emissions[a]			
	$lb/10^6$ ft^3	$kg/10^6$ m^3	lb/hr	kg/hr
Sulfur oxides[b]	0.6	9.6	–	–
Nitrogen oxides[c]	–	–	–	–
Hydrocarbons[d]	1.2	19	4.2	1.9

[a] Reference 1. Values for $lb/10^6$ ft^3 ($kg/10^6$ m^3) based on 3.37×10^6 ft^3/hr heat input.
[b] Based on an average natural gas sulfur content of 2000 $gr/10^6$ ft^3 (4600 $g/10^6$ m^3).
[c] See Figure 3.3.2-1.
[d] Values in Reference 1 were given as tons/day. In converting to lb/hr, 24-hour operation was assumed.

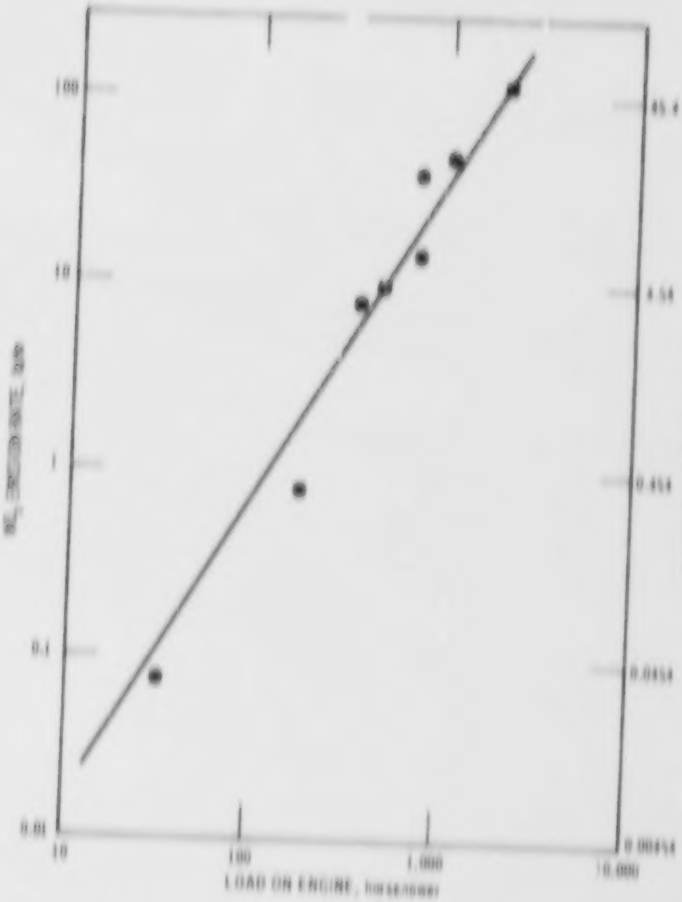

Figure 3.3.2-1. Nitrogen oxides emissions from stationary internal combustion engines.2,3

References for Section 3.3.2

1. Emissions to the Atmosphere from Eight Miscellaneous Sources in Petroleum Refineries. Los Angeles County Air Pollution Control District, Los Angeles, Calif., Report Number VIII. June 1958.

2. Bartok, W., A.R. Crawford, A.R. Cunningham, H.J. Hall, E.H. Manny, and A. Skopp. Systems Study of Nitrogen Oxide Control Methods for Stationary Sources. Final Report-Volume II. Esso Research and Engineering Company. Newark, N.J. Prepared for the National Air Pollution Control Administration, Durham, N.C., under Contract Number PH-22-68-55. November 1969.

3. Mills, J.L., K.D. Leudtke, P.F. Woolrich, and S.B. Perry. Emissions of Oxides of Nitrogen from Stationary Sources in Los Angeles County. Report Number 3. Los Angeles County Air Pollution Control District, Los Angeles, Calif. April 1961.

3.3.3 Gasoline and Diesel Industrial Engines

by David S. Kircher

3.3.3.1 General – This engine category covers a wide variety of industrial applications of both gasoline and diesel internal combustion power plants, such as fork lift trucks, mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The rated power of these engines covers a rather substantial range – from less than 15 kW to 186 kW (20 to 250 hp) for gasoline engines and from 34 kW to 447 kW (45 to 600 hp) for diesel engines. Understandably, substantial differences in both annual usage (hours per year) and engine duty cycles also exist. It was necessary, therefore, to make reasonable assumptions concerning usage in order to formulate emission factors.[1]

3.3.3.2 Emissions – Once reasonable usage and duty cycles for this category were ascertained, emission values from each of the test engines [1] were aggregated (on the basis of nationwide engine population statistics) to arrive at the factors presented in Table 3.3.3-1. Because of their aggregate nature, data contained in this table must be applied to a population of industrial engines rather than to an individual power plant.

The best method for calculating emissions is on the basis of "brake specific" emission factors (g/kWh or lb/hphr). Emissions are calculated by taking the product of the brake specific emission factor, the usage in hours (that is, hours per year or hours per day), the power available (rated power), and the load factor (the power actually used divided by the power available).

Table 3.3.3-1. EMISSION FACTORS FOR GASOLINE- AND DIESEL-POWERED INDUSTRIAL EQUIPMENT
EMISSION FACTOR RATING: C

Pollutant[a]	Engine category[b]	
	Gasoline	Diesel
Carbon monoxide		
g/hr	5700.	197.
lb/hr	12.6	0.434
g/kWh	267.	4.06
g/hphr	199.	3.03
$kg/10^3$ liter	472.	12.2
$lb/10^3$ gal	3940.	102.
Exhaust hydrocarbons		
g/hr	191.	72.8
lb/hr	0.421	0.160
g/kWh	8.95	1.50
g/hphr	6.68	1.12
$kg/10^3$ liter	15.8	4.49
$lb/10^3$ gal	132.	37.5
Evaporative hydrocarbons		
g/hr	62.0	–
lb/hr	0.137	–
Crankcase hydrocarbons		
g/hr	38.3	–
lb/hr	0.084	–

Table 3.3.3-1. (continued). EMISSION FACTORS FOR GASOLINE- AND DIESEL-POWERED INDUSTRIAL EQUIPMENT
EMISSION FACTOR RATING: C

Pollutant[a]	Engine category[b]	
	Gasoline	Diesel
Nitrogen oxides		
g/hr	148.	910.
lb/hr	0.326	2.01
g/kWh	6.92	18.8
g/hphr	5.16	14.0
kg/10^3 liter	12.2	56.2
lb/10^3 gal	102.	469.
Aldehydes		
g/hr	6.33	13.7
lb/hr	0.014	0.030
g/kWh	0.30	0.28
g/hphr	0.22	0.21
kg/10^3 liter	0.522	0.84
lb/10^3 gal	4.36	7.04
Sulfur oxides		
g/hr	7.67	60.5
lb/hr	0.017	0.133
g/kWh	0.359	1.25
g/hphr	0.268	0.931
kg/10^3 liter	0.636	3.74
lb/10^3 gal	5.31	31.2
Particulate		
g/hr	9.33	65.0
lb/hr	0.021	0.143
g/kWh	0.439	1.34
g/hphr	0.327	1.00
kg/10^3 liter	0.775	4.01
lb/10^3 gal	6.47	33.5

[a] References 1 and 2.

[b] As discussed in the text, the engines used to determine the results in this table cover a wide range of uses and power. The listed values do not, however, necessarily apply to some very large stationary diesel engines.

References for Section 3.3.3

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 5: Heavy-Duty Farm, Construction, and Industrial Engines. Southwest Research Institute. San Antonio, Texas. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. October 1973. 105 p.

2. Hare, C. T. Letter to C. C. Masser of the Environmental Protection Agency concerning fuel-based emission rates for farm, construction, and industrial engines. San Antonio, Tex. January 14, 1974.

4. EVAPORATION LOSS SOURCES

Evaporation losses include the organic solvents emitted from dry-cleaning plants and surface-coating operations as well as the volatile matter in petroleum products. This chapter presents the hydrocarbon emissions from these sources, including petroleum storage and gasoline marketing. Where possible, the effect of controls to reduce the emissions of organic compounds has been shown.

4.1 DRY CLEANING

4.1.1 General[1]

Clothing and other textiles may be cleaned by treating them with organic solvents. This treatment process involves agitating the clothing in a solvent bath, rinsing with clean solvent, and drying with warm air.

There are basically two types of dry-cleaning installations: those using petroleum solvents [Stoddard and 140°F (60°C)] and those using chlorinated synthetic solvents (perchloroethylene). The trend in dry-cleaning operations today is toward smaller package operations located in shopping centers and suburban business districts that handle approximately 1500 pounds (675 kg) of clothes per week on the average. These plants almost exclusively use perchloroethylene, whereas the older, larger dry-cleaning plants use petroleum solvents. It has been estimated that perchloroethylene is used on 50 percent of the weight of clothes dry-cleaned in the United States today and that 70 percent of the dry-cleaning plants use perchloroethylene.[2]

4.1.2 Emissions and Controls[1]

The major source of hydrocarbon emissions in dry cleaning is the tumbler through which hot air is circulated to dry the clothes. Drying leads to vaporization of the solvent and consequent emissions to the atmosphere, unless control equipment is used. The primary control element in use in synthetic solvent plants is a water-cooled condenser that is an integral part of the closed cycle in a tumbler or drying system. Up to 95 percent of the solvent that is evaporated from the clothing is recovered here. About half of the remaining solvent is then recovered in an activated-carbon adsorber, giving an overall control efficiency of 97 to 98 percent. There are no commercially available control units for solvent recovery in petroleum-based plants because it is not economical to recover the vapors. Emission factors for dry-cleaning operations are shown in Table 4.1-1.

It has been estimated that about 18 pounds (8.2 kilograms) per capita per year of clothes are cleaned in moderate climates[3] and about 25 pounds (11.3 kilograms) per capita per year in colder areas.[4] Based on this information and the facts that 50 percent of all solvents used are petroleum-based[2] and 25 percent of the synthetic solvent plants are controlled,[5] emission factors can be determined on a pounds- (kilograms-) per-capita basis. Thus approximately 2 pounds (0.9 kilogram) per capita per year are emitted from dry-cleaning plants in moderate climates and 2.7 pounds (1.23 kilograms) per capita per year in colder areas.

Table 4.1-1. HYDROCARBON EMISSION FACTORS FOR DRY CLEANING OPERATIONS
EMISSION FACTOR RATING: C

Control	Petroleum solvents		Synthetic solvents	
	lb/ton	kg/MT	lb/ton	kg/MT
Uncontrolled[a]	305	152.5	210	105
Average control[b]	–	–	95	47.5
Good control[c]	–	–	35	17.5

[a] References 2, 4, 6, and 7.
[b] Reference 6.
[c] Reference 8.

References for Section 4.1

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Communication with the National Institute of Dry Cleaning. 1969.

3. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 46.

4. Dry Cleaning Plant Survey. Michigan Department of Health. Kent County, Michigan. 1965.

5. Communication on dry cleaning plants with S. Landon, Washer Machinery Corporation. June 1968.

6. Chass, R. L., C.V. Kanter, and J.H. Elliot. Contribution of Solvents to Air Pollution and Methods for Controlling Their Emissions. J. Air Pol. Control Assoc. *13*:64-72. February 1963.

7. Bi-State Study of Air Pollution in the Chicago Metropolitan Area. Ill. Dept. of Public Health, Ind. State Board of Health, and Purdue University. Chicago, Illinois. 1957-59.

8. Communication on emissions from dry cleaning plants with A. Netzley. Los Angeles County Air Pollution Control District. Los Angeles, California. July 1968.

4.2 SURFACE COATING

4.2.1 Process Description[1,2]

Surface-coating operations primarily involve the application of paint, varnish, lacquer, or paint primer for decorative or protective purposes. This is accomplished by brushing, rolling, spraying, flow coating, and dipping. Some of the industries involved in surface-coating operations are automobile assemblies, aircraft companies, container manufacturers, furniture manufacturers, appliance manufacturers, job enamelers, automobile repainters, and plastic products manufacturers.

4.2.2 Emissions and Controls[1]

Emissions of hydrocarbons occur in surface-coating operations because of the evaporation of the paint vehicles, thinners, and solvents used to facilitate the application of the coatings. The major factor affecting these emissions is the amount of volatile matter contained in the coating. The volatile portion of most common surface coatings averages approximately 50 percent, and most, if not all, of this is emitted during the application and drying of the coating. The compounds released include aliphatic and aromatic hydrocarbons, alcohols, ketones, esters, alkyl and aryl hydrocarbon solvents, and mineral spirits. Table 4.2-1 presents emission factors for surface-coating operations.

Control of the gaseous emissions can be accomplished by the use of adsorbers (activated carbon) or afterburners. The collection efficiency of activated carbon has been reported at 90 percent or greater. Water curtains or filler pads have little or no effect on escaping solvent vapors; they are widely used, however, to stop paint particulate emissions.

Table 4.2-1. GASEOUS HYDROCARBON EMISSION FACTORS FOR SURFACE COATING APPLICATIONS[a]
EMISSION FACTOR RATING: B

Type of coating	Emissions[b]	
	lb/ton	kg/MT
Paint	1120	560
Varnish and shellac	1000	500
Lacquer	1540	770
Enamel	840	420
Primer (zinc chromate)	1320	660

[a] Reference 1.

[b] Reported as undefined hydrocarbons, usually organic solvents, both aryl and alkyl. Paints weigh 10 to 15 pounds per gallon (1.2 to 1.8 kilograms per liter); varnishes weigh about 7 pounds per gallon (0.84 kilogram per liter).

References for Section 4.2

1. Weiss, S.F. Surface Coating Operations. In: Air Pollution Engineering Manual, Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. p.387-390.

2. Control Techniques for Hydrocarbon and Organic Gases From Stationary Sources. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration. Washington, D.C. Publication Number AP-68. October 1969. Chapter 7.6.

3. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

4.3 STORAGE OF PETROLEUM PRODUCTS

Revised by William M. Vatavuk
and Richard K. Burr

Fundamentally, the petroleum industry consists of three operations (1) crude oil production, (2) petroleum refining, and (3) transportation and marketing of finished products. Associated with these operations are evaporative emissions of various organic compounds, either in pure form or as mixtures.

From an air pollution standpoint, the petroleum industry is defined in terms of two kinds of evaporative losses: (1) storage and (2) marketing and transportation. (See Figure 4.4-1 for schematic of the industry and its points of emission.)

4.3.1 Process Description[1-5]

Petroleum storage evaporation losses are associated with the containment of liquid organics in large vessels at oil fields, refineries, and product distribution terminals.

Six basic tank designs, are used for petroleum storage vessels: (1) fixed roof (cone roof), (2) floating roof (single deck pontoon and double deck), (3) covered floating roof, (4) internal floating cover, (5) variable vapor space, and (6) pressure (low and high).

The fixed roof tank (Figure 4.3-1) is the least expensive vessel for storing certain hydrocarbons and other organics. This tank generally consists of a steel, cylindrical container with a conical roof and is equipped with a pressure/vacuum vent, designed to operate at slight deviations (0.021 Mg/m^2 maximum) from atmospheric pressure.

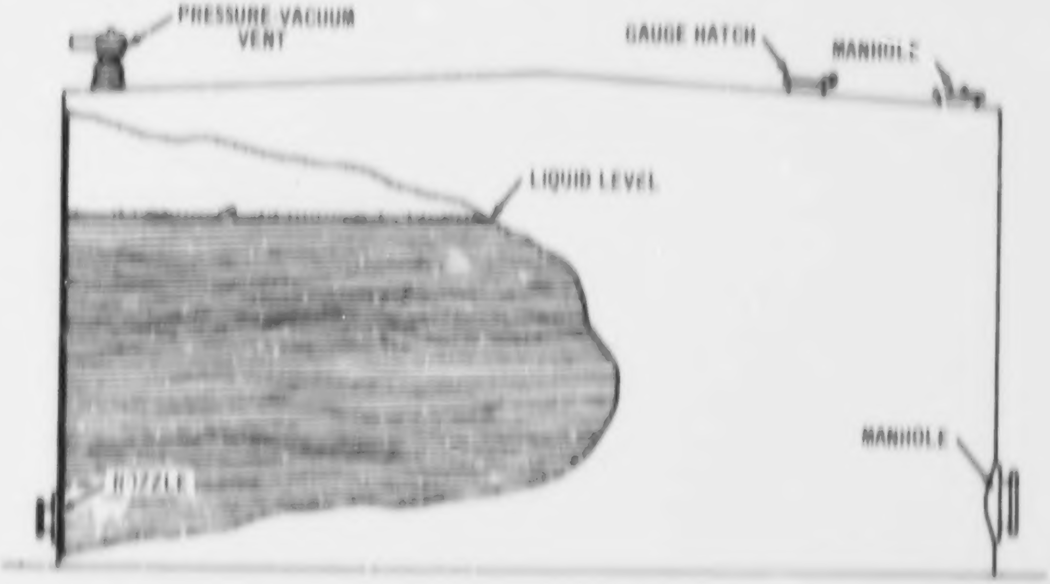

Figure 4.3-1. Fixed roof storage tank.

A floating roof tank is a welded or riveted circular vessel with an external float-type pan or pontoon roof (single- or double-deck) equipped with single or double mechanical seals (Figure 4.3-2).

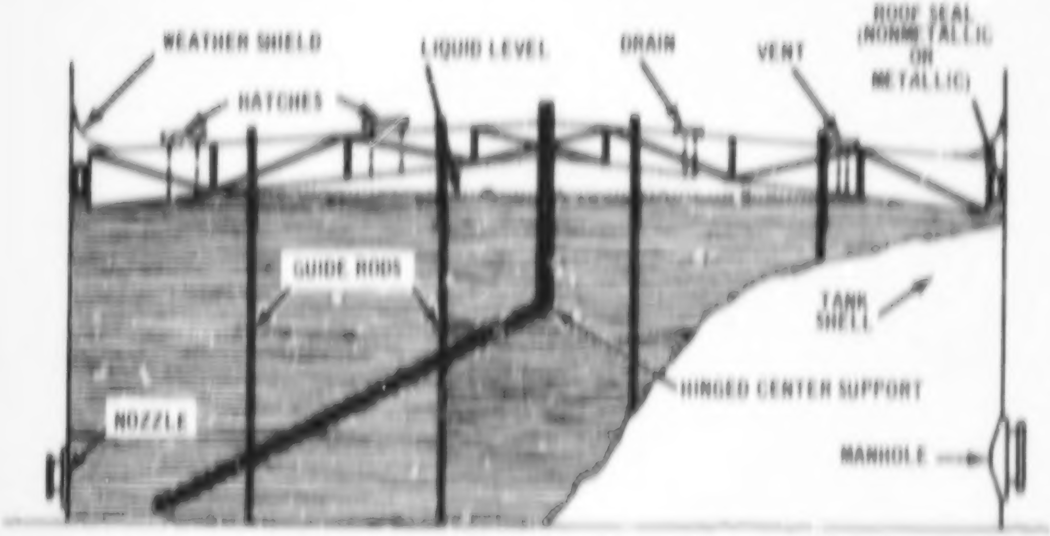

Figure 4.3-2. Double-deck floating roof storage tank (nonmetallic seal).

The floating roof prevents the formation of a volume of organic vapor above the liquid surface, which would otherwise be vented or displaced during filling and emptying. The seal, which is designed to close the annular space between the roof and vessel wall, consists of a relatively thin-gauge shoe ring supported against the tank shell around the roof.

The covered floating roof tank, simply a steel pan-type floating roof inside a fixed roof tank, is designed to reduce product losses and maintenance costs. Another type, the internal floating cover tank, contains a floating cover constructed of a material other than steel. Materials used include aluminum sheeting, glass-fiber-reinforced polyester sheeting, and rigid plastic foam panels.

The lifter and flexible diaphragm variable vapor space tanks are also used to reduce vapor losses (Figure 4.3-3). With the lifter tank, the roof is telescopic; i.e., it can move up or down as the vapor above the liquid surface expands or contracts. Flexible diaphragm tanks serve the same function through the expansion and contraction of a diaphragm.

Pressure tanks are especially designed for the storage of volatile organics under low (17 to 30 psia or 12 to 21 Mg/m^2) or high (up to 265 psia or 186 Mg/m^2) pressure and are constructed in many sizes and shapes, depending on the operating range. The most popular are the noded hemi-spheroid and the noded spheroid for low pressure and the spheroid for high pressure. Horizontal cylindrical forms are also commonly used for high pressure storage.

4.3.2 Emissions and Controls[1-3,5-7]

There are six sources of emissions from petroleum in storage:

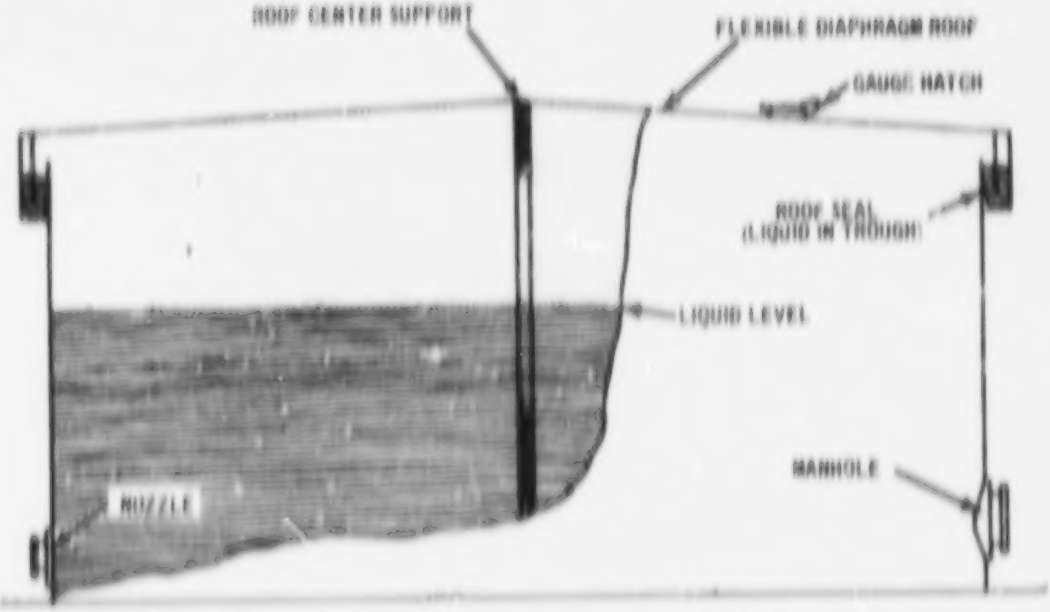

Figure 4.3-3. Variable vapor storage tank (wet-seal lifter type).

Breathing losses are associated with fixed roof tanks and consist of vapor expelled from the tank because of thermal expansion, barometric pressure changes, and added vaporization of the liquid.

Working losses consist of hydrocarbon vapor expelled from the vessel as a result of emptying or filling operations. Filling losses represent the amount of vapor (approximately equal to the volume of liquid input) that is vented to the atmosphere through displacement. After liquid is removed, emptying losses occur, because air drawn in during the operation results in growth of the vapor space. Both filling and emptying (together called "working") losses are associated primarily with fixed roof and variable vapor space tanks. Filling losses are also experienced from low pressure tankage, although to a lesser degree than from fixed roof tanks.

Primarily associated with floating roof tanks, standing storage losses result from the improper fit of the seal and shoe to the tank shell.

Wetting losses with floating roof vessels occur when a wetted tank wall is exposed to the atmosphere. These losses are negligible.

Finally, boiling loss is the vapor expelled when the temperature of the liquid in the tank reaches its boiling point and begins to vaporize.

The quantity of evaporation loss from storage tanks depends on several variables:

(1) True vapor pressure of the liquid stored,
(2) Diurnal temperature changes in the tank vapor space,

(3) Height of the vapor space (tank outage),
(4) Tank diameter,
(5) Schedule of tank fillings and emptyings,
(6) Mechanical condition of tank, and
(7) Type of paint applied to outer surface.

The American Petroleum Institute has developed empirical formulas, based on extensive testing, that correlate breathing, working, and standing storage losses with the above parameters for fixed roof, floating roof, and variable vapor space vessels.

Fixed roof breathing losses can be estimated from:

$$B = \frac{1.74\ WK}{V_t} \left(\frac{P}{14.7-P}\right)^{0.68} D^{1.73}\ H^{0.51}\ \Delta T^{0.50}\ F_p C \qquad (1)$$

where: B = Breathing loss, lb/day-10^3 gal capacity
P = True vapor pressure at bulk liquid temperature, psia
D = Tank diameter, feet
H = Average vapor space height, including correction for roof volume, feet
ΔT = Average daily ambient temperature change, °F
F_p = Paint factor, determined from field tests (see Table 4.3-1)
C = Adjustment factor for tanks smaller than 20 feet in diameter (see Figure 4.3-4)
V_t = Capacity of tank, barrels
K = Factor dependent on liquid stored:
= 0.014 for crude oil
= 0.024 for gasoline
= 0.023 for naphtha jet fuel (JP-4)
= 0.020 for kerosene
= 0.019 for distillate oil
W = Density of liquid at storage conditions, lb/gal

Table 4.3-1. PAINT FACTORS FOR FIXED ROOF TANKS[a]

Tank Color		Paint factor (F_p) Paint condition	
Roof	Shell	Good	Poor
White	White	1.00	1.15
Aluminum (specular)	White	1.04	1.18
White	Aluminum (specular)	1.16	1.24
Aluminum (specular)	Aluminum (specular)	1.20	1.29
White	Aluminum (diffuse)	1.30	1.38
Aluminum (diffuse)	Aluminum (diffuse)	1.39	1.46
White	Gray	1.30	1.38
Light gray	Light gray	1.33	1.44[b]
Medium gray	Medium gray	1.46	1.58[b]

[a] Reference 2.
[b] Estimated from the ratios of the seven preceding paint factors.

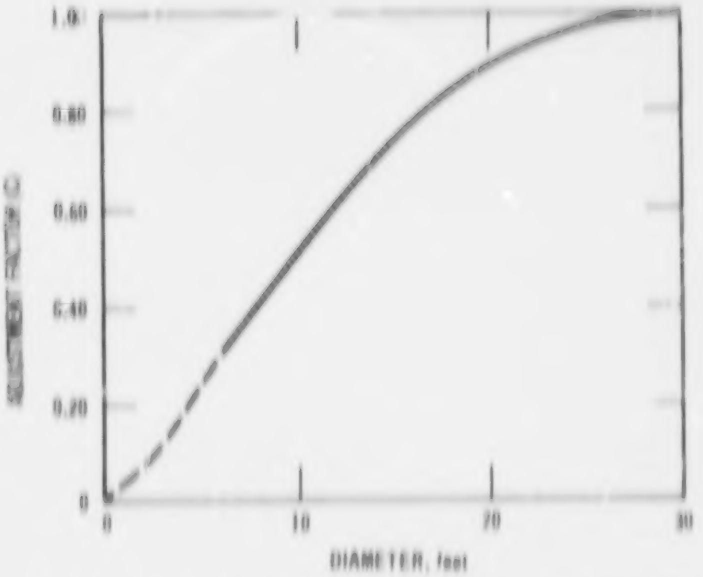

Figure 4.3-4. Adjustment factor for small-diameter fixed roof tanks.[2]

Breathing losses of petrochemicals from fixed roof tanks can be estimated from the respective gasoline loss factor, calculated at their storage temperature:

$$B_p = 0.08 \left(\frac{M_p}{W_G}\right)\left(\frac{P_p}{P_G}\right) B_G \qquad (2)$$

where: B_p, B_G = Breathing losses of petrochemical (p) and gasoline (G), lb/day-10^3 gal

M_p = Molecular weight of petrochemical (p), lb/mole

W = Liquid density of gasoline, lb/gal

P_p, P_G = True vapor pressures of petrochemical (p) and gasoline (G) at their bulk storage temperature, psia

This same correlation can also be used to estimate petrochemical working loss, standing storage loss, or any other kind of loss from any storage tank.

A correlation for fixed roof tank working loss (combined emptying and filling) has also been developed:

$$F_f = 1000\, WmP \left(\frac{180 + N}{6N}\right) \qquad (3)$$

where: F_f = Working loss, lb/10^3 gal throughput

P = True vapor pressure at bulk liquid temperature, psia

N = Number of tank turnovers per year (ratio of annual throughput to tank capacity)

m = Factor dependent on liquid stored:

= 3×10^{-4} for gasoline

= 2.25×10^{-4} for crude oil

= 3.24×10^{-4} for naphtha jet fuel (JP-4)

= 2.95×10^{-4} for kerosene

= 2.76×10^{-4} for distillate oil

Standing storage losses from floating roof tanks can be calculated from:

$$S = \frac{2.74\, W K_t}{V_c} D^{1.5} \left(\frac{P}{14.7 - P}\right)^{0.7} V_w^{0.7} K_s K_c K_p \qquad (4)$$

where: S = Standing storage evaporation loss, lb/day-10^3 gal capacity

K_t = Factor dependent on tank construction:

= 0.045 for welded tank, pan/pontoon roof, single/double seal

= 0.11 for riveted tank, pontoon roof, double seal

= 0.13 for riveted tank, pontoon roof, single seal

= 0.13 for riveted tank, pan roof, double seal

= 0.14 for riveted tank, pan roof, single seal

D = Tank diameter, feet; for $D \geq 150$ feet (45.8 m) use "$D\sqrt{150}$" instead of "$D^{1.5}$"

V_w = Average wind velocity, mi/hr

K_s = Seal factor:

= 1.00 for tight fitting, modern seals

= 1.33 for loose fitting, older seals (typical of pre-1942 installation)

K_c = Factor dependent on liquid stored:

= 1.00 for gasoline

= 0.75 for crude oil

= 0.96 for naphtha jet fuel (JP-4)

= 0.83 for kerosene

= 0.79 for distillate oil

K_p = Paint factor for color of shell and roof:

= 1.00 for light gray or aluminum

= 0.90 for white

Finally, filling losses from variable vapor space systems can be estimated by:

$$F_V = \frac{1000\ WmP}{V_1}\ (V_1 - 0.25V_2N) \qquad (5)$$

where: m = Factor dependent on liquid stored (same as equation 3)

F_V = Filling loss, lb/10^3 gal throughput

V_1 = Volume of liquid throughput, bbl/year

V_2 = Volume of expansion capacity, barrels

N = Number of turnovers per year

W = Density of liquid at storage conditions, lb/gal

Equations 1 through 5 can be used to calculate evaporative losses, provided the respective parameters are known. For those cases where such quantities are unknown or for quick loss estimates, however, Table 4.3-2 provides typical emission factors. Refinement of emission estimates by using these loss correlations may be desirable in areas where these sources contribute a substantial portion of the total evaporative emissions or are of major consequence in affecting the air quality.

The control methods most commonly used with fixed roof tanks are vapor recovery systems, which collect emissions from storage vessels and send them to gas recovery plants. The four recovery methods used are liquid absorption, vapor compression, vapor condensation, and adsorption in activated charcoal or silica gel.

Overall control efficiencies of vapor recovery systems vary from 90 to 95 percent, depending on the method used, the design of the unit, the organic compounds recovered, and the mechanical condition of the system.

In addition, water sprays, mechanical cooling, underground liquid storage, and optimum scheduling of tank turnovers are among the techniques used to minimize evaporative losses by reducing tank heat input.

Table 4.3-2. EVAPORATIVE EMISSION
EMISSION FACTOR

Product	Vapor pressure ratio (P/P_O)	Mole wt (M) (lb/mole)	Floating roof			
			Standing storage loss			
			"New tank" conditions		"Old tank" conditions	
			lb/day / 10^3 gal	kg/day / 10^3 liter	lb/day / 10^3 gal	kg/day / 10^3 liter
Crude oil[c]		64.5	0.029	0.0034	0.071	0.0085
Gasoline[c]		56.8	0.033	0.0040	0.088	0.011
Naphtha jet fuel (JP-4)[c]		63.3	0.012	0.0014	0.029	0.0034
Kerosene[c]		72.7	0.0052	0.00063	0.012	0.0015
Distillate fuel[c]		72.7	0.0052	0.00063	0.012	0.0015
Acetone	0.543	58.1	0.014	0.0017	0.036	0.0043
Ammonium hydroxide (28.8 % solution)	1.53	35.1	0.023	0.0028	0.062	0.0074
Benzene[c]	0.2108	78.1	0.0074	0.00089	0.020	0.0023
Isobutyl alcohol	0.0263	74.1	0.00086	0.00010	0.0023	0.00028
Tertbutyl alcohol	0.0843	74.1	0.0028	0.00034	0.0074	0.00089
Carbon tetrachloride	0.264	153.8	0.018	0.0021	0.048	0.0057
Cyclohexane[c]	0.230	84.2	0.0083	0.0010	0.022	0.0027
Cyclopentane[c]	0.776	70.1	0.024	0.0028	0.062	0.0074
Ethyl acetate	0.210	88.1	0.0081	0.00097	0.021	0.0025
Ethyl alcohol	0.120	46.1	0.0024	0.00029	0.0064	0.00074
Freon II	2.01	137.4	0.12	0.014	0.32	0.038
n-Heptane[c]	0.103	100.2	0.0045	0.00054	0.012	0.0014
n-Hexane[c]	0.353	86.2	0.013	0.0016	0.036	0.0043
Hydrogen cyanide	1.42	27.0	0.017	0.0020	0.043	0.00051
Isooctane[c]	0.112	114.2	0.0055	0.00066	0.015	0.0018
Isopentane[c]	1.86	72.2	0.057	0.0069	0.15	0.018
Isopropyl alcohol	0.0833	60.1	0.0024	0.00029	0.0064	0.00077
Methyl alcohol	0.272	32.0	0.0038	0.00046	0.010	0.0012
n-Pentane[c]	1.26	72.2	0.038	0.0046	0.10	0.012
Toluene[c]	0.0604	92.1	0.0024	0.00029	0.0062	0.00074

[a] References 2, 3, 6, and 7.

[b] Factors based on following conditions:

Storage temperature: 63°F (17.2°C).
Daily ambient temperature change: 15°F (-9.5°C).
Wind velocity: 10 mi/hr (4.5 m/sec).

	Reid vapor pressure		True vapor pressure	
	psia	Mg/m^2	psia	Mg/m^2
Crude oil	7.0	4.9	4.6	3.2
Gasoline	10.5	7.4	5.8	4.1
Naphtha jet fuel (JP-4)	2.5	1.76	1.2	0.84
Kerosene	<0.5	<0.35	<0.5	<0.35
Distillate oil	<0.5	<0.35	<0.5	<0.35

Typical fixed- and floating-roof tanks:

Diameter: 90 ft (27.4 m) for crude, JP-4, kerosene, and distillate; 110 ft (33.5 m) for gasoline and all petrochemicals.
Height: 44 ft (13.4 m) for crude, JP-4, kerosene, and distillate; 48 ft (14.6 m) for gasoline and all petrochemicals.
Capacity: 50,000 bbl (7.95 × 10^6 liter) for crude, JP-4, kerosene, and distillate; 67,000 bbl (10.65 × 10^6 liter) for gasoline and all petrochemicals.
Outage: 50 percent of tank height.
Turnovers per year: 30 for crude oil; 13 for all others.

[c] Indicates petroleum products whose evaporative emissions are exclusively hydrocarbons (i.e., compounds containing only the elements hydrogen and carbon).

FACTORS FOR STORAGE TANKS[a, b]
RATING: A

Fixed roof						Variable vapor space	
Breathing loss				Working loss		Working loss	
"New tank" conditions		"Old tank" conditions					
lb/day 10³ gal	kg/day 10³ liter	lb/day 10³ gal	kg/day 10³ liter	lb/10³ gal throughput	kg/10³ liter throughput	lb/10³ gal throughput	kg/10³ liter throughput
0.15	0.018	0.17	0.020	7.3	0.88	Not used	Not used
0.22	0.026	0.25	0.031	9.0	1.1	10.2	1.2
0.069	0.0083	0.079	0.0095	2.4	0.29	2.3	0.28
0.036	0.0043	0.041	0.0048	1.0	0.12	1.0	0.12
0.036	0.0043	0.041	0.0048	1.0	0.12	1.0	0.12
0.093	0.011	0.10	0.013	3.7	0.45	4.2	0.51
0.16	0.018	0.18	0.021	6.3	0.76	7.1	0.86
0.050	0.0057	0.057	0.0069	2.0	0.24	2.3	0.27
0.0057	0.00067	0.0064	0.0079	0.23	0.028	0.26	0.031
0.018	0.0021	0.021	0.0026	0.74	0.090	0.83	0.099
0.12	0.014	0.14	0.016	4.8	0.58	5.4	0.65
0.057	0.0067	0.064	0.0079	2.3	0.28	2.6	0.31
0.16	0.019	0.18	0.022	6.4	0.77	7.2	0.87
0.055	0.0066	0.062	0.0074	2.2	0.27	2.5	0.30
0.016	0.0019	0.018	0.0022	0.65	0.078	0.73	0.088
0.81	0.098	0.92	0.11	32.4	3.9	36.7	4.4
0.031	0.0036	0.033	0.0040	1.2	0.15	1.4	0.16
0.088	0.010	0.10	0.012	3.6	0.43	4.0	0.48
0.11	0.013	0.13	0.016	4.5	0.54	5.1	0.61
0.036	0.0043	0.043	0.0051	1.5	0.18	1.7	0.21
0.39	0.047	0.45	0.053	15.7	1.9	17.8	2.1
0.016	0.0019	0.019	0.0022	0.66	0.080	0.74	0.090
0.026	0.0031	0.029	0.0034	1.0	0.13	1.2	0.14
0.26	0.032	0.30	0.036	10.6	1.3	12.0	1.4
0.016	0.0019	0.018	0.022	0.64	0.077	0.73	0.087

Typical floating-roof tank
Paint factor (K_p): New tank white paint, 0.90; Old tank white/aluminum paint, 0.95.
Seal factor (K_s): New tank modern seals, 1.00; Old tank 50 percent old seals, 1.14.
Tank factor (K_t): New tank welded, 0.045; Old tank 50 percent riveted, 0.088.

Typical fixed-roof tank
Paint factor (F_p): New tank white paint, 1.00; Old tank white/aluminum paint, 1.14.

Typical variable vapor space tank
Diameter: 50 ft (15.2 m).
Height: 30 ft (9.2 m).
Capacity: 10,500 bbl (1.67 × 10⁶ liter).
Turnovers per year: 6.

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4.4 MARKETING AND TRANSPORTATION OF PETROLEUM PRODUCTS

by William M. Vatavuk

4.4.1 Process Description[1]

As Figure 4.4-1 indicates, the marketing and transportation of petroleum products involves many distinct operations, each of which can represent a source of evaporation loss.

For example, after gasoline is refined, it is transported first via pipeline, rail, ship, or barge to intermediate storage and then to regional marketing terminals for temporary storage in large quantities. From here, the product is pumped into tank trucks that deliver it directly to service stations or to larger distributors at "bulk plants." From bulk plants, the product is delivered, again in trucks, to commercial accounts (e.g., trucking companies). The final destination for the gasoline is normally a motor vehicle gas tank. A similar distribution path may be developed for fuel oil and other petroleum products.

4.4.2 Emissions and Controls[2-5]

Losses from marketing and transportation fall into five categories, depending on the storage equipment or mode of conveyance used:

1. Large storage tanks: Breathing, working, and standing storage losses;
2. Railroad tank cars and tank trucks: Loading and unloading losses;
3. Marine vessels: Loading, unloading, and transit losses;
4. Service stations: Loading and unloading losses from tank trucks and underground tanks; and
5. Motor vehicle tanks: Refueling losses.

(In addition, evaporative (and exhaust) emissions are also associated with motor vehicle operation. These topics are discussed in Chapter 3.)

Losses from large storage tanks have been thoroughly discussed in section 4.3.

Unloading losses from tank cars and trucks consist of the amount of organic liquid that evaporates into the air that is drawn in during a complete withdrawal of the contents of a tank compartment. These losses can be estimated (within ± 10 percent) using the following expression derived from American Petroleum Institute correlations:

$$U_L = \frac{69{,}600\ YPW}{(690-4M)T} \qquad (1)$$

where: U_L = Unloading loss, lb/10^3 gal of liquid loaded

Y = Degree of saturation of organic in vapor space at time of unloading (estimated or measured)

T = Bulk absolute temperature of organic liquid, °R

P = True vapor pressure of liquid at temperature (T), psia

M = Molecular weight of liquid, lb/lb mole

W = Density of hydrocarbon liquid at temperature (T), lb/gal

The quantity of loading losses is directly dependent on the filling method used. "Splash" loading, which usually results in extremely high emissions, occurs when the liquid is discharged into the upper part of a container through a short filler spout. This free fall of the liquid encourages both evaporation and entrainment loss caused by the formation and expulsion of liquid droplets. In "subsurface" or "submerged" loading, lower emissions are achieved because the liquid is delivered directly to the bottom of the tank through a tightly connected pipe/spout without splashing.

A submerged loading loss correlation (generally accurate within ± 25 percent) based on equation 1 has also been developed:

$$L_{sub} = \left(\frac{1.00-Y}{2}\right) \frac{69{,}600\ PW}{(690-4M)T} \qquad (2)$$

where: L_{sub} = Submerged loading loss, lb/10^3 gal of liquid loaded

Y = Saturation of the existent vapor in tank before loading

This relationship assumes that the vapor formed during unloading (existent vapor) remains in the tank until the next loading. Then the additional liquid that evaporates during loading becomes the loading loss. (A more rapid method for calculating loading and unloading losses has been developed by the American Petroleum Institute.[6])

Variables affecting splash loading loss include the loading rate, the degree of saturation of existent vapor, and the elevation and angle of the loading spout. The following correlation was derived from the American Petroleum Institute empirical formula:

$$L_{sp} = \frac{(1.023 \times 10^{6})W}{(690-4M)T} \left[\frac{14.7 - YP}{14.7 - (0.95)P} - 1\right] \qquad (3)$$

where: L_{sp} = Splash loading loss, lb/10^3 gal

In equation (3), the vapor displaced from the tank is assumed to be 95 percent saturated—quite reasonable in view of the high degree of saturation observed in vapors from splash-filling operations. The accuracy of this expression is found to be ± 10 percent, 90 percent of the time.

Finally, transit (breathing) losses from tank cars and trucks during product shipment is assumed to be negligible because the travel time is relatively short (2 days or less).

Emission correlations have also been developed for marine vessels.

For unloading losses:

$$U_L = 0.07PW \qquad (4)$$

where: U_L = Unloading loss, lb/10^3 gal of load

P = True vapor pressure of liquid at storage temperature, psia

W = Density of liquid at storage temperature, lb/gal

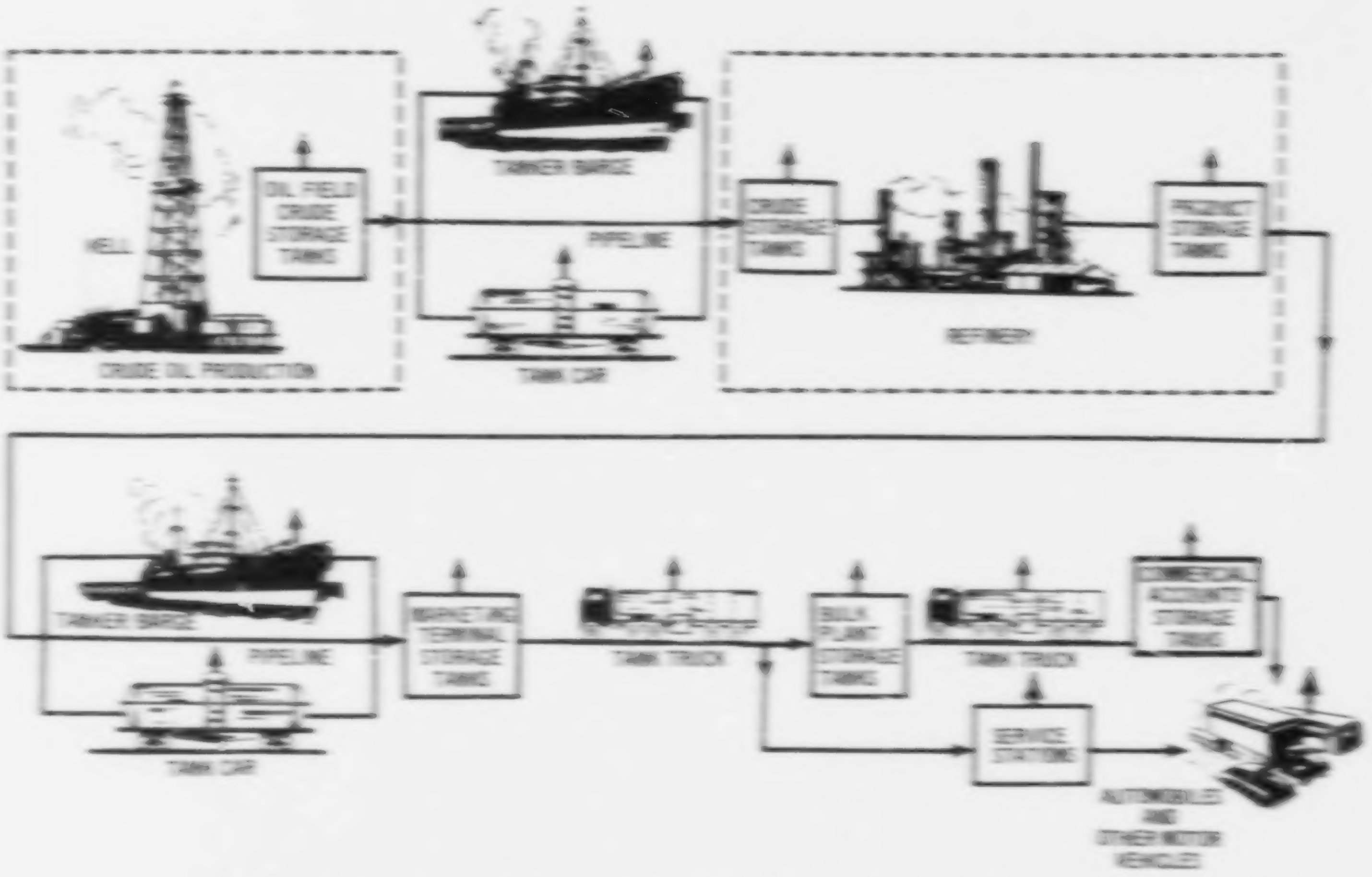
WELL
OIL FIELD CRUDE STORAGE TANKS
CRUDE OIL PRODUCTION
TANKER BARGE
PIPELINE
TANK CAR
CRUDE STORAGE TANKS
REFINERY
PRODUCT STORAGE TANKS
TANKER BARGE
PIPELINE
TANK CAR
MARKETING TERMINAL STORAGE TANKS
TANK TRUCK
BULK PLANT STORAGE TANKS
TANK TRUCK
COMMERCIAL ACCOUNTS STORAGE TANKS
SERVICE STATIONS
AUTOMOBILES AND OTHER MOTOR VEHICLES

Figure 4.4-1. Flowsheet of petroleum production, refining, and distribution systems. (Sources of organic evaporative emissions are indicated by vertical arrows.)

For loading:

$$L_S = 0.08PW \qquad (5)$$

where: L_S = Loading loss, lb/10^3 gal of load

Since vessel shipments are transported for longer periods, transit losses can be substantial. These losses can be estimated by the following:

$$R_S = 0.1PW \qquad (6)$$

where: R_S = Transit loss, lb/10^3 gal of load per week

For quick reference, selected petroleum product emission factors for transportation sources are provided in Table 4.4-1.

A fourth major source of evaporative emissions is the loading and unloading of underground gasoline storage tanks at service stations. As with the other categories, the quantity of the loading losses depends on several variables such as the size and length of the fill pipe; the method of filling; the tank configuration; as well as the gasoline temperature, vapor pressure, and composition. Depending on these parameters, and the control method used, loading losses can vary from 0 to 11.5 lb/10^3 gal (1.4 kg/10^3 liter) of gasoline pumped into the tank (see Table 4.4-1).

Unloading losses from underground tanks result from the inhalation of air and exhalation of a vapor-air mixture during normal pumping operations. Variables affecting the losses are the type of service station operation, the gasoline pumping rate and frequency, the ratio of liquid surface to vapor volume, the diffusion and mixing of gasoline vapors and air, as well as the other parameters mentioned previously (Table 4.4-1).

The final loss category to be considered is the splash filling of motor vehicle gasoline tanks. These losses consist of vapor displacement (94 percent of total loss) from the vehicle tank and liquid spillage (6 percent of total) as the gasoline is pumped.

Scott Research Inc., under an EPA contract, did extensive laboratory and field testing that resulted in the development of an empirical vapor displacement formula:[3]

$$L_D = 2.22 \exp(-0.02645 + 0.01155T_{DF} - 0.01226T_V + 0.00246T_VP_{RVP}) \qquad (7)$$

where: L_D = Vapor displacement loss, lb/10^3 gal

T_{DF} = Average dispensed fuel temperature, °F

T_V = Average temperature of vehicle tank vapor displaced, °F

P_{RVP} = Reid vapor pressure of gasoline pumped, taken at storage temperature and composition, psia

exp = Base of natural logarithms = 2.71828

This expression provides good loss estimates ($\pm$ 0.5 lb/10^3 gal or 0.06 kg/10^3 liter) within the experimental temperature interval of 30° to 90°F (-1.1° to 32.2 °C).

The quantity of spillage loss is a function of the type of service station, vehicle tank configuration, operator technique, and operation discomfort indices. An overall average of 0.67 lb/10^3 gal (0.081 kg/10^3 liter) has been estimated (Table 4.4-1).

Control methods for transportation and marketing sources are similar to those utilized with large storage tanks and generally consist of one or more types of vapor recovery systems located at transfer terminals. Depending on the system and the compounds recovered, the overall control efficiencies range from 90 to 95 percent.

For example, a technique used with some underground gasoline storage tanks consists of an arrangement by which vapors are recycled to the tank trucks during filling operations through the annular space of a specially designed "interlock valve" and into a side arm that is connected to the return manifold in the dome cap of the truck (see Figure 4.4-2). The control efficiency of this method ranges from 93 to 100 percent when compared with uncontrolled, splash fill loading (see Table 4.4-1).

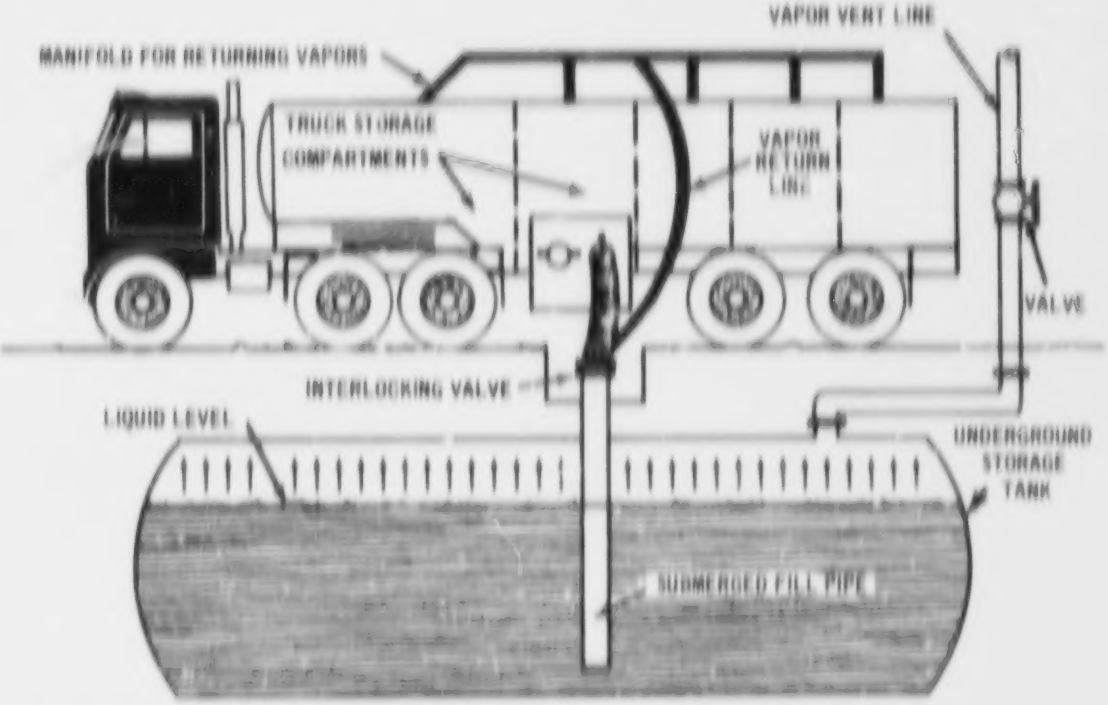
VAPOR VENT LINE
MANIFOLD FOR RETURNING VAPORS
TRUCK STORAGE COMPARTMENTS
VAPOR RETURN LINE
VALVE
INTERLOCKING VALVE
LIQUID LEVEL
UNDERGROUND STORAGE TANK
SUBMERGED FILL PIPE

Figure 4.4-2. Underground storage tank vapor-recovery system[1].

Table 4.4-1. ORGANIC COMPOUND EVAPORATIVE EMISSION FACTORS FOR PETROLEUM TRANSPORTATION AND MARKETING SOURCES[a]

EMISSION FACTOR RATING: A

Emission source	Product				
	Gasoline	Crude oil	Naphtha jet fuel (JP-4)	Kerosene	Distillate oil
Tank cars/trucks[b]					
Splash loading					
lb/10^3 gal transferred	12.4	10.6	1.8	0.88	0.93
kg/10^3 liter transferred	1.5	1.3	0.22	0.11	0.11
Submerged loading					
lb/10^3 gal transferred	4.1	4.0	0.91	0.45	0.48
kg/10^3 liter transferred	0.49	0.48	0.11	0.054	0.058
Unloading					
lb/10^3 gal transferred	2.1	2.0	0.45	0.23	0.24
kg/10^3 liter transferred	0.25	0.24	0.054	0.028	0.029
Marine vessels[b]					
Loading					
lb/10^3 gal transferred	2.9	2.6	0.60	0.27	0.29
kg/10^3 liter transferred	0.35	0.31	0.072	0.032	0.035
Unloading					
lb/10^3 gal transferred	2.5	2.3	0.52	0.24	0.25
kg/10^3 liter transferred	0.30	0.28	0.062	0.029	0.030
Transit					
lb/wk-10^3 gal load	3.6	3.2	0.74	0.34	0.36
kg/wk-10^3 liter load	0.43	0.38	0.089	0.041	0.043
Underground gasoline storage tanks[c]					
Splash loading					
lb/10^3 gal transferred	11.5	NU[d]	NU	NU	NU
kg/10^3 liter transferred	1.4	NU	NU	NU	NU
Uncontrolled submerged loading					
lb/10^3 gal transferred	7.3	NU	NU	NU	NU
kg/10^3 liter transferred	0.88	NU	NU	NU	NU
Submerged loading with open vapor return system					
lb/10^3 gal transferred	0.80	NU	NU	NU	NU
kg/10^3 liter transferred	0.097	NU	NU	NU	NU
Submerged loading with closed vapor return system					
lb/10^3 gal transferred	Neg	NU	NU	NU	NU
kg/10^3 liter transferred	Neg	NU	NU	NU	NU

Table 4.4-1 (continued). ORGANIC COMPOUND EVAPORATIVE EMISSION FACTORS FOR PETROLEUM TRANSPORTATION AND MARKETING SOURCES
EMISSION FACTOR RATING: A

Emission source	Product Gasoline	Crude oil	Naphtha jet fuel (JP 4)	Kerosene	Distillate Oil
Unloading					
lb/10^3 gal transferred	1.0	NU	NU	NU	NU
kg/10^3 liter transferred	0.12	NU	NU	NU	NU
Filling motor vehicle gasoline tanks[e]					
Vapor displacement loss					
lb/10^3 gal pumped	11.0	NU	NU	NU	NU
kg/10^3 liter pumped	1.3	NU	NU	NU	NU
Liquid spillage loss					
lb/10^3 gal pumped	0.67	NU	NU	NU	NU
kg/10^3 liter pumped	0.081	NU	NU	NU	NU

[a] References 1, 3, and 5.

[b] Data based on the following conditions:

Storage temperature: 63 °F (17.2 °C)
Saturation of tank (existent vapors) in loading and unloading tank
trucks and cars: 20 percent

	Gasoline	Crude oil	Naphtha jet fuel (JP 4)	Kerosene	Distillate oil
Molecular weight of vapor, lb/lb-mole	66.8	64.5	63.3	72.7	72.7
Reid vapor pressure					
psia	10.5	7.0	2.5	0.5	0.5
Mg/m^2	7.4	4.9	1.75	0.35	0.35
True vapor pressure					
psia	5.8	4.6	1.2	0.5	0.5
Mg/m^2	4.1	3.2	0.84	0.35	0.35
Liquid density					
lb/gal	6.2	7.0	6.2	6.8	7.2
kg/liter	0.74	0.84	0.74	0.82	0.87

[c] Factors for underground gasoline storage tanks based on an organic compound vapor space concentration of 40 percent by volume, which corresponds to a saturation of nearly 100 percent.

[d] Not used.

[e] Motor vehicle gasoline tank vapor displacement factor based on an average dispensed fuel temperature of 63 °F (17.2 °C), an average displaced vapor temperature of 67 °F (19.4 °C), and a Reid vapor pressure of 10.5 psia (7.4 Mg/m^2).

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5. CHEMICAL PROCESS INDUSTRY

This section deals with emissions from the manufacture and use of chemicals or chemical products. Potential emissions from many of these processes are high, but because of the nature of the compounds they are usually recovered as an economic necessity. In other cases, the manufacturing operation is run as a closed system allowing little or no escape to the atmosphere.

In general, the emissions that reach the atmosphere from chemical processes are primarily gaseous and are controlled by incineration, adsorption, or absorption. In some cases, particulate emissions may also be a problem. The particulates emitted are generally extremely small and require very efficient treatment for removal. Emission data from chemical processes are sparse. It was therefore frequently necessary to make estimates of emission factors on the basis of material balances, yields, or similar processes.

5.1 ADIPIC ACID

5.1.1 Process Description[1]

Adipic acid, $COOH\text{-}(CH_2)_4\text{-}COOH$, is a dibasic acid used in the manufacture of synthetic fibers. The acid is made in a continuous two-step process. In the first step, cyclohexane is oxidized by air over a catalyst to a mixture of cyclohexanol and cyclohexanone. In the second step, adipic acid is made by the catalytic oxidation of the cyclohexanol-cyclohexanone mixture using 45 to 55 percent nitric acid. The final product is then purified by crystallization.[2]

5.1.2 Emissions

The only significant emissions from the manufacture of adipic acid are nitrogen oxides. In oxidizing the cyclohexanol/cyclohexanone, nitric acid is reduced to unrecoverable N_2O and potentially recoverable NO and NO_2. This NO and NO_2 can be emitted into the atmosphere. Table 5.1-1 shows typical emissions of NO and NO_2 from an adipic acid plant.

Table 5.1-1. EMISSION FACTORS FOR AN ADIPIC ACID PLANT WITHOUT CONTROL EQUIPMENT
EMISSION FACTOR RATING: D

Source	Nitrogen oxides (NO, NO_2)	
	lb/ton	kg/MT
Oxidation of cyclohexanol/cyclohexanone[a]	12	6

[a] Reference 1.

References for Section 5.1

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5.2 AMMONIA

5.2.1 Process Description[1]

The manufacture of ammonia (NH_3) is accomplished primarily by the catalytic reaction of hydrogen and nitrogen at high temperatures and pressures. In a typical plant a hydrocarbon feed stream (usually natural gas) is desulfurized, mixed with steam, and catalytically reformed to carbon monoxide and hydrogen. Air is introduced into the secondary reformer to supply oxygen and provide a nitrogen to hydrogen ratio of 1 to 3. The gases then enter a two-stage shift converter that allows the carbon monoxide to react with water vapor to form carbon dioxide and hydrogen. The gas stream is next scrubbed to yield a gas containing less than 1 percent CO_2. A methanator may be used to convert quantities of unreacted CO to inert CH_4 before the gases, now largely nitrogen and hydrogen in a ratio of 1 to 3, are compressed and passed to the converter. Alternatively, the gases leaving the CO_2 scrubber may pass through a CO scrubber and then to the converter. The synthesis gases finally react in the converter to form ammonia.

5.2.2 Emissions and Controls[1]

When a carbon monoxide scrubber is used before sending the gas to the converter, the regenerator offgases contain significant amounts of carbon monoxide (73 percent) and ammonia (4 percent). This gas may be scrubbed to recover ammonia and then burned to utilize the CO fuel value.[2]

The converted ammonia gases are partially recycled, and the balance is cooled and compressed to liquefy the ammonia. The noncondensable portion of the gas stream, consisting of unreacted nitrogen, hydrogen, and traces of inerts such as methane, carbon monoxide, and argon, is largely recycled to the converter. To prevent the accumulation of these inerts, however, some of the noncondensable gases must be purged from the system.

The purge or bleed-off gas stream contains about 15 percent ammonia.[2] Another source of ammonia is the gases from the loading and storage operations. These gases may be scrubbed with water to reduce the atmospheric emissions. In addition, emissions of CO and ammonia can occur from plants equipped with CO scrubbing systems. Emission factors are presented in Table 5.2-1.

Table 5.2-1. EMISSION FACTORS FOR AMMONIA MANUFACTURING WITHOUT CONTROL EQUIPMENT[a]
EMISSION FACTOR RATING: B

Type of source	Carbon monoxide		Hydrocarbons[b]		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Plants with methanator						
Purge gas[c]	Neg	Neg	90	45	3	1.5
Storage and loading[c]	–	–	–	–	200	100
Plants with CO absorber and regeneration system						
Regenerator exit[d]	200	100	–	–	7	3.5
Purge gas[c]	Neg	Neg	90	45	3	1.5
Storage and loading[c]	–	–	–	–	200	100

[a] References 2 and 3.

[b] Expressed as methane.

[c] Ammonia emissions can be reduced by 99 percent by passing through three stages of a packed-tower water scrubber. Hydrocarbons are not reduced.

[d] A two-stage water scrubber and incineration system can reduce these emissions to a negligible amount.

References for Section 5.2

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Reston, Virginia. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Burns, W.E. and R.R. McMullan. No Noxious Ammonia Odor Here. Oil and Gas Journal. p. 129-131, February 25, 1967.

3. Axelrod, L.C. and T.E. O'Hare. Production of Synthetic Ammonia. New York, M.W. Kellogg Company. 1964.

5.3 CARBON BLACK

Carbon black is produced by the reaction of hydrocarbon fuel such as oil or gas, or both, with a limited supply of air at temperatures of 2500° to 3000°F (1370° to 1650°C). Part of the fuel is burned to CO_2, CO, and water, thus generating heat for the combustion of fresh feed. The unburned carbon is collected as a black fluffy particle. The three basic processes for producing this compound are the furnace process, accounting for about 83 percent of production; the older channel process, which accounts for about 6 percent of production; and the thermal process.

5.3.1 Channel Black Process[1]

In the channel black process, natural gas is burned with a limited air supply in long, low buildings. The flame from this burning impinges on long steel channel sections that swing continuously over the flame. Carbon black is deposited on the channels, is scraped off, and falls into collecting hoppers. The combustion gases containing the solid carbon that is not collected on the channels, in addition to carbon monoxide and other combustion products, are then vented directly from the building. Approximately 1 to 1.5 pounds of carbon black is produced from the 32 pounds of carbon available in 1000 cubic feet of natural gas (16 to 24 kilograms carbon black from the 513 kilograms [illegible] 1000 cubic meters).[2,3] The balance is lost as CO, CO_2, hydrocarbons, and particulates.

5.3.2 Furnace Process[1]

The furnace process is subdivided into either the gas or oil process depending on the primary fuel used to produce the carbon black. In either case, the fuel (gas in the gas process or gas and oil in the oil process) is injected into a reactor with a limited supply of combustion air. The combustion gases containing the hot carbon are then rapidly cooled to a temperature of about 500°F (260°C) by water sprays and by radiant cooling.

The largest and most important portion of the furnace process consists of the particulate or carbon black removal equipment. While many combinations of control equipment exist, an electrostatic precipitator, a cyclone, and a fabric filter system in series are most commonly used to collect the carbon black. Gaseous emissions of carbon monoxide and hydrocarbons are not controlled in the United States.

5.3.3 Thermal Black Process[1]

In thermal black plants, natural gas is decomposed by heat in the absence of air or flame. In this cyclic operation, methane is pyrolyzed or decomposed by passing it over a heated brick checkerwork at a temperature of about 3000°F (1650°C). The decomposed gas is then cooled and the carbon black removed by a series of cyclones and fabric filters. The exit gas, consisting largely of hydrogen (85 percent), methane (5 percent), and nitrogen, is then either recycled to the process burners or used to generate steam in a boiler. Because of the recycling of the effluent gases, there are essentially no atmospheric emissions from this process, other than from product handling.

Table 5.3-1 presents the emission factors from the various carbon black processes. Nitrogen oxide emissions are not included but are believed to be low because of the lack of available oxygen in the reaction.

Table 5.3-1. EMISSION FACTORS FOR CARBON BLACK MANUFACTURING[a]
EMISSION FACTOR RATING: C

Type of process	Particulate		Carbon monoxide		Hydrogen sulfide		Hydrocarbons[b]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Channel	2,300	1,150	33,500	16,750	–	–	11,500	5,750
Thermal	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg
Furnace								
Gas	c	c	5,300	2,650	–	–	1,800	900
Oil	c	c	4,500	2,250	35S[d]	17.5S[d]	400	200
Gas or oil	220[e] 60[f] 10[g]	110[e] 30[f] 5[g]						

[a] Based on data in References 2, 3, 5, and 6.

[b] As methane.

[c] Particulate emissions cannot be separated by type of furnace and are listed for either gas or oil furnaces.

[d] S is the weight percent sulfur in feed.

[e] Overall collection efficiency was 90 percent with no collection after cyclone.

[f] Overall collection efficiency was 97 percent with cyclones followed by scrubber.

[g] Overall collection efficiency was 99.5 percent with fabric filter system.

References for Section 5.3

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Reston, Virginia. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Drogin, I. Carbon Black. J. Air Pol. Control Assoc. *18*:216-228, April 1968.

3. Cox, J.T. High Quality, High Yield Carbon Black. Chem. Eng. *57*:116-117, June 1950.

4. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 124-130.

5. Reinke, R.A. and T.A. Ruble. Oil Black. Ind. Eng. Chem. *44*:685-694, April 1952.

6. Allan, D. L. The Prevention of Atmospheric Pollution in the Carbon Black Industry. Chem. Ind. p. 1320-1324, October 15, 1955.

5.4 CHARCOAL

5.4.1 Process Description[1]

Charcoal is generally manufactured by means of pyrolysis, or destructive distillation, of wood waste from members of the deciduous hardwood species. In this process, the wood is placed in a retort where it is externally heated for about 20 hours at 500° to 700°F (260° to 370°C). Although the retort has air intakes at the bottom, these are only used during start-up and thereafter are closed. The entire distillation cycle takes approximately 24 hours, the last 4 hours being an exothermic reaction. Four units of hardwood are required to produce one unit of charcoal.

5.4.2 Emissions and Controls[1]

In the pyrolysis of wood, all the gases, tars, oils, acids, and water are driven off, leaving virtually pure carbon. All of these except the gas, which contains methane, carbon monoxide, carbon dioxide, nitrogen oxides, and aldehydes, are useful by-products if recovered. Unfortunately, economics has rendered the recovery of the distillate by-products unprofitable, and they are generally permitted to be discharged to the atmosphere. If a recovery plant is utilized, the gas is passed through water-cooled condensers. The condensate is then refined while the remaining cool, noncondensable gas is discharged to the atmosphere. Gaseous emissions can be controlled by means of an afterburner because the unrecovered by-products are combustible. If the afterburner operates efficiently, no organic pollutants should escape into the atmosphere. Emission factors for the manufacture of charcoal are shown in Table 5.4-1.

Table 5.4-1. EMISSION FACTORS FOR CHARCOAL MANUFACTURING[a]
EMISSION FACTOR RATING: C

	Type of operation			
	With chemical recovery plant		Without chemical recovery plant	
Pollutant	lb/ton	kg/MT	lb/ton	kg/MT
Particulate (tar, oil)	–	–	400	200
Carbon monoxide	320[b]	160[b]	320[b]	160[b]
Hydrocarbons[c]	100[b]	50[b]	100[b]	50[b]
Crude methanol	–	–	152	76
Acetic acid	–	–	232	116
Other gases (HCHO, N_2, NO)	60	30	60[b]	30[b]

[a] Calculated values based on data in Reference 2.
[b] Emissions are negligible if afterburner is used.
[c] Expressed as methane.

References for Section 5.4

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 619.

5.5 CHLOR-ALKALI

5.5.1 Process Description[1]

Chlorine and caustic are produced concurrently by the electrolysis of brine in either the diaphragm or mercury cell. In the diaphragm cell, hydrogen is liberated at the cathode and a diaphragm is used to prevent contact of the chlorine produced at the anode with either the alkali hydroxide formed or the hydrogen. In the mercury cell, liquid mercury is used as the cathode and forms an amalgam with the alkali metal. The amalgam is removed from the cell and is allowed to react with water in a separate chamber, called a denuder, to form the alkali hydroxide and hydrogen.

Chlorine gas leaving the cells is saturated with water vapor and then cooled to condense some of the water. The gas is further dried by direct contact with strong sulfuric acid. The dry chlorine gas is then compressed for in-plant use or is cooled further by refrigeration to liquefy the chlorine.

Caustic as produced in a diaphragm-cell plant leaves the cell as a dilute solution along with unreacted brine. The solution is evaporated to increase the concentration to a range of 50 to 73 percent; evaporation also precipitates most of the residual salt, which is then removed by filtration. In mercury-cell plants, high-purity caustic can be produced in any desired strength and needs no concentration.

5.5.2 Emissions and Controls[1]

Emissions from diaphragm- and mercury-cell chlorine plants include chlorine gas, carbon dioxide, carbon monoxide, and hydrogen. Gaseous chlorine is present in the blow gas from liquefaction, from vents in tank cars and tank containers during loading and unloading, and from storage tanks and process transfer tanks. Other emissions include mercury vapor from mercury cathode cells and chlorine from compressor seals, header seals, and the air blowing of depleted brine in mercury-cell plants.

Chlorine emissions from chlor-alkali plants may be controlled by one of three general methods: (1) use of the gas in other plant processes, (2) neutralization in alkaline scrubbers, and (3) recovery of chlorine from effluent gas streams. The effect of specific control practices is shown to some extent in the table on emission factors (Table 5.5-1).

References for Section 5.5

1. Atmospheric Emissions from Chlor-Alkali Manufacture. U.S. EPA, Air Pollution Control Office. Research Triangle Park, N.C. Publication Number AP-80. January 1971.

2. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 49.

Table 5.5-1. EMISSION FACTORS FOR CHLOR-ALKALI PLANTS[a]
EMISSION FACTOR RATING: B

Type of source	Chlorine gas	
	lb/100 tons	kg/100 MT
Liquefaction blow gases		
Diaphragm cell, uncontrolled	2,000 to 10,000	1,000 to 5,000
Mercury cell[b], uncontrolled	4,000 to 16,000	2,000 to 8,000
Water absorber	25 to 1,000	12.5 to 500
Caustic or lime scrubber	1	0.5
Loading of chlorine		
Tank car vents	450	225
Storage tank vents	1,200	600
Air blowing of mercury cell brine	500	250

[a] References 1 and 2.

[b] Mercury cells lose about 1.5 pounds mercury per 100 tons (0.75 kg/100 MT) of chlorine liquefied.

5.6 EXPLOSIVES

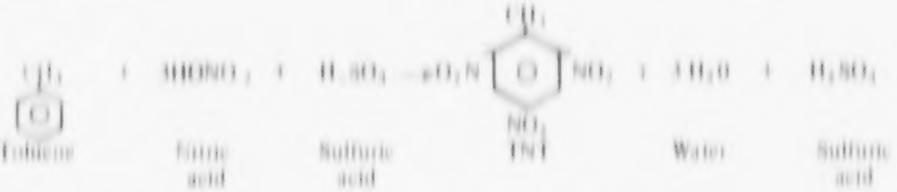
by Charles Mann

5.6.1 General[1]

An explosive is a material that, under the influence of thermal or mechanical shock, decomposes rapidly and spontaneously with the evolution of large amounts of heat and gas. Explosives fall into two major categories: high explosives and low explosives. High explosives are further subdivided into initiating or primary high explosives and secondary high explosives. Initiating high explosives are very sensitive and are generally used in small quantities in detonators and percussion caps to set off larger quantities of secondary high explosives. Secondary high explosives, chiefly nitrates, nitro compounds, and nitramines, are much less sensitive to mechanical or thermal shock, but explode with great violence when set off by an initiating explosive. The chief secondary high explosives manufactured for commercial and military use are ammonium nitrate blasting agents and 2,4,6-trinitrotoluene (TNT). Low explosives, such as black powder and nitrocellulose, undergo relatively slow autocombustion when set off and evolve large volumes of gas in a definite and controllable manner. A multitude of different types of explosives are manufactured. As examples of the production of a high explosive and a low explosive, the production of TNT and nitrocellulose are discussed in this section.

5.6.2 TNT Production[1-3]

TNT may be prepared by either a continuous process or a batch, three-stage nitration process using toluene, nitric acid, and sulfuric acid as raw materials. In the batch process, a mixture of oleum (fuming sulfuric acid) and nitric acid that has been concentrated to a 97 percent solution is used as the nitrating agent. The overall reaction may be expressed as:



(1)

Spent acid from the nitration vessels is fortified with make-up 60 percent nitric acid before entering the next nitrator. Fumes from the nitration vessels are collected and removed from the exhaust by an oxidation-absorption system. Spent acid from the primary nitrator is sent to the acid recovery system in which the sulfuric and nitric acid are separated. The nitric acid is recovered as a 60 percent solution, which is used for refortification of spent acid from the second and third nitrators. Sulfuric acid is concentrated in a drum concentrator by boiling water out of the dilute acid. The product from the third nitration vessel is sent to the wash house at which point asymmetrical isomers and incompletely nitrated compounds are removed by washing with a solution of sodium sulfite and sodium hydrogen sulfite (Sellite). The wash waste (commonly called red water) from the purification process is discharged directly as a liquid waste stream, is collected and sold, or is concentrated to a slurry and incinerated in rotary kilns. The purified TNT is solidified, granulated, and moved to the packing house for shipment or storage. A schematic diagram of TNT production by the batch process is shown in Figure 5.6-1.

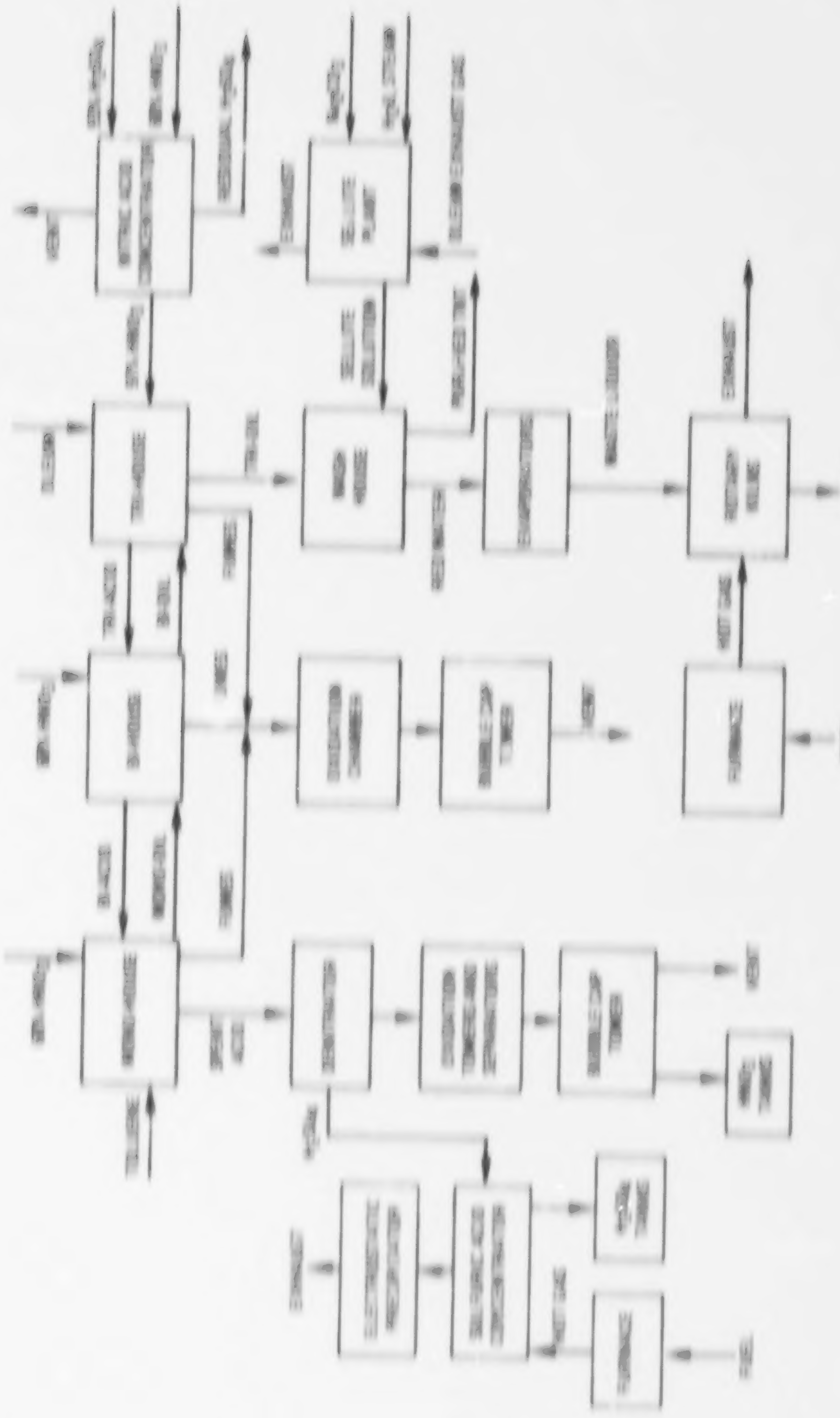


Figure 5.6-1. Flow diagram of typical batch process TNT plant.

5.6.3 Nitrocellulose Production[1]

Nitrocellulose is prepared by the batch-type "mechanical dipper" process. Cellulose, in the form of cotton linters, fibers, or specially prepared wood pulp, is purified, bleached, dried, and sent to a reactor (niter pot) containing a mixture of concentrated nitric acid and a dehydrating agent such as sulfuric acid, phosphoric acid, or magnesium nitrate. The overall reaction may be expressed as:

$$\underset{\text{Cellulose}}{C_6H_7O_2(OH)_3} + \underset{\text{Nitric acid}}{3HONO_2} + \underset{\text{Sulfuric acid}}{H_2SO_4} \longrightarrow \underset{\text{Nitrocellulose}}{C_6H_7O_2(ONO_2)_3} + \underset{\text{Water}}{3H_2O} + \underset{\text{Sulfuric acid}}{H_2SO_4} \qquad (2)$$

When nitration is complete, the reaction mixtures are centrifuged to remove most of the spent acid. The spent acid is fortified and reused or otherwise disposed of. The centrifuged nitrocellulose undergoes a series of water washings and boiling treatments for purification of the final product.

5.6.4 Emissions and Controls[2,3,5]

The major emissions from the manufacture of explosives are nitrogen oxides and acid mists, but smaller amounts of sulfuric oxides and particulates may also be emitted. Emissions of nitrobodies (nitrated organic compounds) may also occur from many of the TNT process units. These compounds cause objectionable odor problems and act to increase the concentration of acid mists. Emissions of sulfur oxides and nitrogen oxides from the production of nitric acid and sulfuric acid used for explosives manufacturing can be considerable. It is imperative to identify all processes that may take place at an explosives plant in order to account for all sources of emissions. Emissions from the manufacture of nitric and sulfuric acid are discussed in other sections of this publication.

In the manufacture of TNT, vents from the fume recovery system, sulfuric acid concentrators, and nitric acid concentrators are the principal sources of emissions. If open burning or incineration of waste explosives is practiced, considerable emissions may result. Emissions may also result from the production of Sellite solution and the incineration of red water. Many plants, however, now sell the red water to the paper industry where it is of economic importance.

Principal sources of emissions from nitrocellulose manufacture are from the reactor pots and centrifuges, spent acid concentrators, and boiling tubs used for purification.

The most important factor affecting emissions from explosives manufacture is the type and efficiency of the manufacturing process. The efficiency of the acid and fume recovery systems for TNT manufacture will directly affect the atmospheric emissions. In addition, the degree to which acids are exposed to the atmosphere during the manufacturing process affects the NO_x and SO_x emissions. For nitrocellulose production, emissions are influenced by the nitrogen content and the desired quality of the final product. Operating conditions will also affect emissions. Both TNT and nitrocellulose are produced in batch processes. Consequently, the processes may never reach steady state and emission concentrations may vary considerably with time. Such fluctuations in emissions will influence the efficiency of control methods. Several measures may be taken to reduce emissions from explosives manufacturing. The effects of various control devices and process changes upon emissions, along with emission factors for explosives manufacturing, are shown in Table 5.6-1. The emission factors are all related to the amount of product produced and are appropriate for estimating long-term emissions or for evaluating plant operation at full production conditions. For short time periods or for plants with intermittent operating schedules, the emission factors in Table 5.6-1 should be used with caution, because processes not associated with the nitration step are often not in operation at the same time as the nitration reactor.

Table 5.6-1. EMISSION FACTORS FOR

EMISSION FACTOR

Type of process	Particulates		Sulfur oxides (SO_2)	
	lb/ton	kg/MT	lb/ton	kg/MT
TNT - batch process[b]				
Nitration reactors				
Fume recovery	-	-	-	-
Acid recovery	-	-	-	-
Nitric acid concentrators	-	-	-	-
Sulfuric acid concentrators[c]				
Electrostatic precipitator (exit)	-	-	14(4-40)	7(2-20)
Electrostatic precipitator with scrubber[d]	-	-	Neg	Neg
Red water incinerator				
Uncontrolled[e]	25(0.03-126)	12.5(0.015-63)	2(0.05-3.5)	1(0.025-1.75)
Wet scrubber[f]	1	0.5	2(0.05-3.5)	1(0.025-1.75)
Sellite exhaust	-	-	59(0.01-177)	29.5(0.005-88)
TNT - continuous process[g]				
Nitration reactors				
Fume recovery	-	-	-	-
Acid recovery	-	-	-	-
Red water incinerator	0.25(0.03-0.05)	0.13(0.015-0.025)	0.24(0.05-0.43)	0.12(0.025-0.22)
Nitrocellulose[g]				
Nitration reactors[h]	-	-	1.4(0.8-2)	0.7(0.4-1)
Nitric acid concentrator	-	-	-	-
Sulfuric acid concentrator	-	-	68(0.4-135)	34(0.2-67)
Boiling tubs	-	-	-	-

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[a] For some processes considerable variations in emissions have been reported. The average of the values reported is shown first, with the ranges given in parentheses. Where only one number is given, only one source test was available.

[b] Reference 6.

[c] Acid mist emissions influenced by nitrobody levels and type of fuel used in furnace.

[d] No data available for NO_x emissions after the scrubber. It is assumed that NO_x emissions are unaffected by the scrubber.

EXPLOSIVES MANUFACTURING[a]
RATING: C

Nitrogen oxides (NO_2)		Nitric acid mist (100% HNO_3)		Sulfuric acid mist (100% H_2SO_4)	
lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
25(6-38)	12.5(3-19)	1(0.3-1.9)	0.5(0.15-0.95)	—	—
55(1-136)	27.5(0.5-68)	92(0.01-275)	46(0.005-137)	—	—
37(16-72)	18.5(8-36)	—	—	9(0.3-27)	4.5(0.15-13.5)
40(2-80)	20(1-40)	—	—	65(1-188)	32.5(0.5-94)
40(2-80)	20(1-40)	—	—	5(4-6)	2.5(2-3)
26(1.5-101)	13(0.75-50)	—	—	—	—
5	2.5	—	—	—	—
		—	—	6(0.6-16)	3(0.3-8)
8(6.7-10)	4(3.35-5)	1(0.3-1.9)	0.5(0.15-0.95)	—	—
3(1-4.5)	1.5(0.5-2.25)	0.02(0.01-0.03)	0.01(0.005-0.015)	—	—
7(6.1-8.4)	3.5(3-4.2)	—	—	—	—
14(3.7-34)	7(1.85-17)	19(0.5-36)	9.5(0.25-18)	—	—
14(10-18)	7(5-9)	—	—	—	—
		—	—	0.3	0.3
2	1	—	—	—	—

[e] Use low end of range for modern, efficient units and high end of range for older, less efficient units.

[f] Apparent reductions in NO_x and particulate after control may not be significant because these values are based on only one test result.

[g] Reference 4.

[h] For product with low nitrogen content (12 percent), use high end of range. For products with higher nitrogen content, use lower end of range.

References for Section 5.6

1. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 383-393.

2. Unpublished data on emissions from explosives manufacturing. National Air Pollution Control Administration, Office of Criteria and Standards. Durham, N.C. June 1970.

3. Higgins, F.B., Jr., et al. Control of Air Pollution From TNT Manufacturing. (Presented at 60th annual meeting of Air Pollution Control Association. Cleveland. June 1967. Paper 67-111.)

4. Air Pollution Engineering Source Sampling Surveys, Radford Army Ammunition Plant. U.S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

5. Air Pollution Engineering Source Sampling Surveys, Volunteer Army Ammunition Plant and Joliet Army Ammunition Plant. U.S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

5.7 HYDROCHLORIC ACID

Hydrochloric acid is manufactured by a number of different chemical processes. Approximately 80 percent of the hydrochloric acid, however, is produced by the by-product hydrogen chloride process, which will be the only process discussed in this section. The synthesis process and the Mannheim process are of secondary importance.

5.7.1 Process Description[1]

By-product hydrogen chloride is produced when chlorine is added to an organic compound such as benzene, toluene, and vinyl chloride. Hydrochloric acid is produced as a by-product of this reaction. An example of a process that generates hydrochloric acid as a by-product is the direct chlorination of benzene. In this process benzene, chlorine, hydrogen, air, and some trace catalysts are the raw materials that produce chlorobenzene. The gases from the reaction of benzene and chlorine consist of hydrogen chloride, benzene, chlorobenzenes, and air. These gases are first scrubbed in a packed tower with a chilled mixture of monochlorobenzene and dichlorobenzene to condense and recover any benzene or chlorobenzene. The hydrogen chloride is then absorbed in a falling film absorption plant.

5.7.2 Emissions

The recovery of the hydrogen chloride from the chlorination of an organic compound is the major source of hydrogen chloride emissions. The exit gas from the absorption or scrubbing system is the actual source of the hydrogen chloride emitted. Emission factors for hydrochloric acid produced as by-product hydrogen chloride are presented in Table 5.7-1.

Table 5.7-1. EMISSION FACTORS FOR HYDROCHLORIC ACID MANUFACTURING[a]
EMISSION FACTOR RATING: B

Type of process	Hydrogen chloride emissions	
	lb/ton	kg/MT
By-product hydrogen chloride		
With final scrubber	0.2	0.1
Without final scrubber	3	1.5

[a] Reference 1.

Reference for Section 5.7

1. Atmospheric Emissions from Hydrochloric Acid Manufacturing Processes. U.S. DHEW, PHS, CPEHS, National Air Pollution Control Administration. Durham, N.C. Publication Number AP-54. September 1969.

5.8 HYDROFLUORIC ACID

5.8.1 Process Description[1]

All hydrofluoric acid in the United States is currently produced by the reaction of acid-grade fluorspar with sulfuric acid for 30 to 60 minutes in externally fired rotary kilns at a temperature of 400° to 500°F (204° to 260°C).[2,3,4] The resulting gas is then cleaned, cooled, and absorbed in water and weak hydrofluoric acid to form a strong acid solution. Anhydrous hydrofluoric acid is formed by distilling 80 percent hydrofluoric acid and condensing the gaseous HF which is driven off.

5.8.2 Emissions and Controls[1]

Air pollutant emissions are minimized by the scrubbing and absorption systems used to purify and recover the HF. The initial scrubber utilizes concentrated sulfuric acid as a scrubbing medium and is designed to remove dust, SO_2, SO_3, sulfuric acid mist, and water vapor present in the gas stream leaving the primary dust collector. The exit gases from the final absorber contain small amounts of HF, silicon tetrafluoride (SiF_4), CO_2, and SO_2 and may be scrubbed with a caustic solution to reduce emissions further. A final water ejector, sometimes used to draw the gases through the absorption system, will reduce fluoride emissions. Dust emissions may also result from raw fluorspar grinding and drying operations. Table 5.8-1 lists the emission factors for the various operations.

Table 5.8-1. EMISSION FACTORS FOR HYDROFLUORIC ACID MANUFACTURING[a]
EMISSION FACTOR RATING: E

Type of operation	Fluorides		Particulates	
	lb/ton acid	kg/MT acid	lb/ton fluorspar	kg/MT fluorspar
Rotary kiln				
Uncontrolled	50	25		
Water scrubber	0.2	0.1		
Grinding and drying of fluorspar			20[b]	10[b]

[a] References 5 and 6.
[b] Factor given for well-controlled plant.

References for Section 5.8

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc., Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Rogers, W.E. and K. Muller. Hydrofluoric Acid Manufacture. Chem. Eng. Progr. 59:85-88, May 1963.

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5.9 NITRIC ACID

Revised by William Vatavuk

5.9.1 Process Description

5.9.1.1 Weak Acid Production[1] - Nearly all the nitric acid produced in the United States is manufactured by the high-pressure catalytic oxidation of ammonia (Figure 5.9-1). Typically, this process consists of three steps, each of which corresponds to a distinct chemical reaction. First, a 1:9 ammonia-air mixture is oxidized at high temperature and pressure (6.4 to 9.2 atmospheres), as it passes through a platinum-rhodium catalyst, according to the reaction:

$$\underset{\text{Ammonia}}{4NH_3} + \underset{\text{Oxygen}}{5O_2} \rightarrow \underset{\text{Nitric oxide}}{4NO} + \underset{\text{Water}}{6H_2O} \qquad (1)$$

After the process stream is cooled to 100°F (38°C) or less by passage through a cooler-condenser, the nitric oxide reacts with residual oxygen:

$$2NO + O_2 \rightarrow \underset{\text{Nitrogen dioxide}}{2NO_2} \rightleftharpoons \underset{\text{Nitrogen tetroxide}}{N_2O_4} \qquad (2)$$

Finally, the gases are introduced into a bubble-cap plate absorption column where they are contacted with a countercurrent stream of water. The exothermic reaction that occurs is:

$$3NO_2 + H_2O \rightarrow \underset{\substack{\text{Nitric acid} \\ \text{50 to 70\% aqueous}}}{2HNO_3} + NO \qquad (3)$$

The production of nitric oxide in reaction (3) necessitates the introduction of a secondary air stream into the column to effect its oxidation to nitrogen dioxide, thereby perpetuating the absorption operation.

The spent gas flows from the top of the absorption tower to an entrainment separator for acid-mist removal, through the ammonia oxidation unit for energy absorption from the ammonia stream, through an expander for energy recovery, and finally to the stack. In most plants the stack gas is treated before release to the atmosphere by passage through either a catalytic combustor or, less frequently, an alkaline scrubber.

5.9.1.2 High-Strength Acid Production[1] - To meet requirements for high-strength acid, the 50 to 70 percent acid produced by the pressure process is concentrated to 95 to 99 percent at approximately atmospheric pressure. The concentration process consists of feeding strong sulfuric acid and 60 percent nitric acid to the top of a packed column where it is contacted by an ascending stream of weak acid vapor, resulting in the dehydration of the latter. The concentrated acid vapor that leaves the column passes to a bleacher and countercurrent condenser system to effect condensation of the vapors and separation of the small amounts of nitric oxides and oxygen that form as dehydration by-products. These by-products then flow to an absorption column where the nitric oxide mixes with auxiliary air to form nitrogen dioxide, which is, in turn, recovered as weak nitric acid. Finally, unreacted gases are vented to the atmosphere from the top of the column.

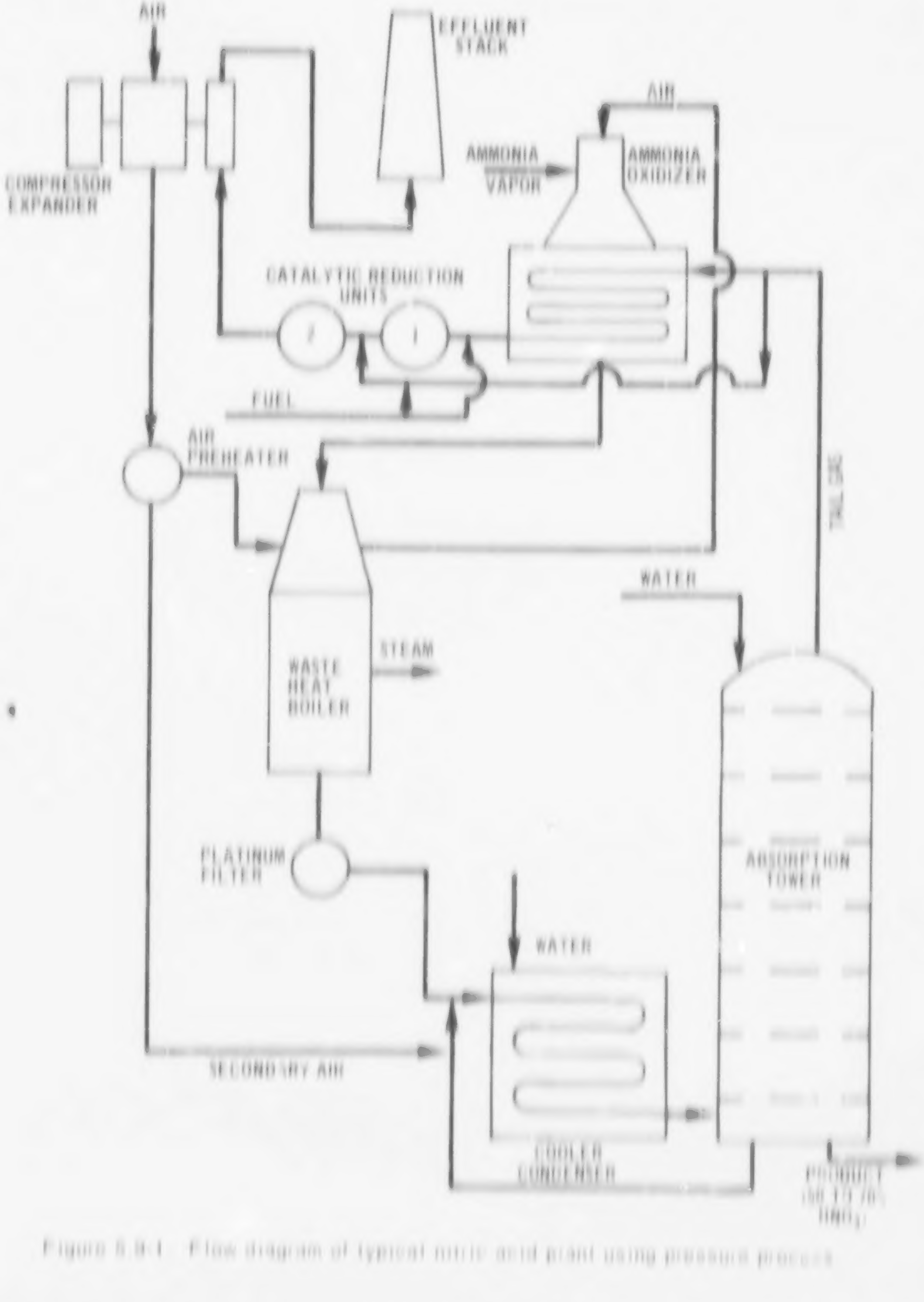
AIR
EFFLUENT STACK
COMPRESSOR
EXPANDER
AIR
AMMONIA VAPOR
AMMONIA OXIDIZER
CATALYTIC REDUCTION UNITS
2
1
FUEL
AIR PREHEATER
TAIL GAS
WATER
WASTE HEAT BOILER
STEAM
PLATINUM FILTER
ABSORPTION TOWER
WATER
SECONDARY AIR
COOLER CONDENSER
PRODUCT (50 TO 70% HNO3)

Figure 5.9-1. Flow diagram of typical nitric acid plant using pressure process.

5.9.2 Emissions and Controls[1-3]

The emissions derived from nitric acid manufacture consist primarily of nitric oxide, which accounts for visible emissions; nitrogen dioxide; and trace amounts of nitric acid mist. By far, the major source of nitrogen oxides is the tail gas from the acid absorption tower (Table 5.9-1). In general, the quantity of NO_x emissions is directly related to the kinetics of the nitric acid formation reaction.

The specific operating variables that increase tail gas NO_x emissions are: (1) insufficient air supply, which results in incomplete oxidation of NO; (2) low pressure in the absorber; (3) high temperature in the cooler-condenser and absorber; (4) production of an excessively high-strength acid; and (5) operation at high throughput rates, which results in decreased residence time in the absorber.

Aside from the adjustment of these variables, the most commonly used means for controlling emissions is the catalytic combustor. In this device, tail gases are heated to ignition temperature, mixed with fuel (natural gas, hydrogen, or a mixture of both), and passed over a catalyst. The reactions that occur result in the successive reduction of NO_2 to NO and, then, NO to N_2. The extent of reduction of NO_2 to N_2 in the combustor is, in turn, a function of plant design, type of fuel used, combustion temperature and pressure, space velocity through the combustor, type and amount of catalyst used, and reactant concentrations (Table 5.9-1).

Comparatively small amounts of nitrogen oxides are also lost from acid concentrating plants. These losses (mostly NO_2) occur from the condenser system, but the emissions are small enough to be easily controlled by the installation of inexpensive absorbers.

Table 5.9-1. NITROGEN OXIDE EMISSIONS FROM NITRIC ACID PLANTS[a]
EMISSION FACTOR RATING: B

Type of control	Control efficiency, %	Emissions (NO_2)[b] lb/ton acid	Emissions (NO_2)[b] kg/MT acid
Weak acid			
Uncontrolled	0	50 to 55[c]	25.0 to 27.5
Catalytic combustor (natural gas fired)	78 to 97	2 to 7[d]	1.0 to 3.5
Catalytic combustor (hydrogen fired)	97 to 99.8	0.0 to 1.5	0.0 to 0.75
Catalytic combustor (75% hydrogen, 25% natural gas fired)	98 to 98.5	0.8 to 1.1	0.4 to 0.55
High-strength acid		0.2 to 5.0	0.1 to 2.5

[a] References 1 and 2.

[b] Based on 100 percent acid production.

[c] Range of values taken from four plants measured at following process conditions: production rate, 120 tons (108 MT) per day (100 percent rated capacity); absorber exit temperature, 90°F (32°C); absorber exit pressure, 7.8 atmospheres; acid strength, 57 percent. Under different conditions, values can vary from 43 to 57 lb/ton (21.5 to 28.5 kg/MT).

[d] To present a more realistic picture, ranges of values were used instead of averages.

Acid mist emissions do not occur from a properly operated plant. The small amounts that may be present in the absorber exit gas stream are removed by a separator or collector prior to entering the catalytic combustor or expander.

Finally, small amounts of nitrogen dioxide are lost during the filling of storage tanks and tank cars.

Nitrogen oxide emissions (expressed as NO_2) are presented for weak nitric acid plants in table 5.9-1. The emission factors vary considerably with the type of control employed, as well as with process conditions. For comparison purposes, the Environmental Protection Agency (EPA) standard for both new and modified plants is 3.0 pounds per ton of 100 percent acid produced (1.5 kilograms per metric ton), maximum 2-hour average, expressed as NO_2.[4] Unless specifically indicated as 100 percent acid, production rates are generally given in terms of the total weight of product (water and acid). For example, a plant producing 500 tons (454 MT) per day of 55 weight percent nitric acid is really producing only 275 tons (250 MT) per day of 100 percent acid.

References for Section 5.9

1. Control of Air Pollution from Nitric Acid Plants. Unpublished Report. Environmental Protection Agency, Research Triangle Park, N.C.

2. Atmospheric Emissions from Nitric Acid Manufacturing Processes. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. Publication Number 999-AP-27. 1966.

3. Unpublished emission data from a nitric acid plant. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration, Office of Criteria and Standards. Durham, N.C. June 1970.

4. Standards of Performance for New Stationary Sources. Environmental Protection Agency, Washington, D.C. Federal Register. 36(247): December 23, 1971.

5.10 PAINT AND VARNISH

5.10.1 Paint Manufacturing[1]

The manufacture of paint involves the dispersion of a colored oil or pigment in a vehicle, usually an oil or resin, followed by the addition of an organic solvent for viscosity adjustment. Only the physical processes of weighing, mixing, grinding, tinting, thinning, and packaging take place; no chemical reactions are involved.

These processes take place in large mixing tanks at approximately room temperature.

The primary factors affecting emissions from paint manufacture are care in handling dry pigments, types of solvents used, and mixing temperature.[2,3] About 1 or 2 percent of the solvents is lost even under well-controlled conditions. Particulate emissions amount to 0.5 to 1.0 percent of the pigment handled.[4]

5.10.2 Varnish Manufacturing[1,3]

The manufacture of varnish also involves the mixing and blending of various ingredients to produce a wide range of products. However, in this case chemical reactions are initiated by heating. Varnish is cooked in either open or enclosed gas-fired kettles for periods of 4 to 16 hours at temperatures of 200° to 650°F (93° to 340°C).

Varnish cooking emissions, largely in the form of organic compounds, depend on the cooking temperatures and times, the solvent used, the degree of tank enclosure, and the type of air pollution controls used. Emissions from varnish cooking range from 1 to 6 percent of the raw material.

To reduce hydrocarbons from the manufacture of paint and varnish, control techniques include condensers and/or adsorbers on solvent-handling operations, and scrubbers and afterburners on cooking operations. Emission factors for paint and varnish are shown in Table 5.10-1.

Table 5.10-1. EMISSION FACTORS FOR PAINT AND VARNISH MANUFACTURING WITHOUT CONTROL EQUIPMENT[a,b] EMISSION FACTOR RATING: C

Type of product	Particulate		Hydrocarbons[c]	
	lb/ton pigment	kg/MT pigment	lb/ton of product	kg/MT pigment
Paint	2	1	30	15
Varnish				
Bodying oil			40	20
Oleoresinous			150	75
Alkyd			160	80
Acrylic			20	10

[a] References 2 and 4 through 8.

[b] Afterburners can reduce gaseous hydrocarbon emissions by 99 percent and particulates by about 90 percent. A water spray and oil filter system can reduce particulates by about 90 percent.[8]

[c] Expressed as undefined organic compounds whose composition depends upon the type of varnish or paint.

References for Section 5.10

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C. under Contract Number CPA-22-69-119. April 1970.

2. Stenburg, R.L. Atmospheric Emissions from Paint and Varnish Operations. Paint Varn. Prod. p. 61-65 and 111-114, September 1959.

3. Private Communication between Resources Research, Incorporated, and National Paint, Varnish and Lacquer Association. September 1969.

4. Unpublished engineering estimates based on plant visits in Washington, D.C. Resources Research, Incorporated. Reston, Va. October 1969.

5. Chatfield, H.E. Varnish Cookers. In: Air Pollution Engineering Manual. Danielson, J. A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 688-695.

6. Lunche, R.G. et al. Distribution Survey of Products Emitting Organic Vapors in Los Angeles County. Chem. Eng. Progr. 53. August 1957.

7. Communication on emissions from paint and varnish operations with G. Sallee. Midwest Research Institute. December 17, 1969.

8. Communication with Roger Higgins. Benjamin Moore Paint Company. June 25, 1968.

5.11 PHOSPHORIC ACID

Phosphoric acid is produced by two principal methods, the wet process and the thermal process. The wet process is usually employed when the acid is to be used for fertilizer production. Thermal-process acid is normally of higher purity and is used in the manufacture of high-grade chemical and food products.

5.11.1 Wet Process[1,2]

In the wet process, finely ground phosphate rock is fed into a reactor with sulfuric acid to form phosphoric acid and gypsum. There is usually little market for the gypsum produced, and it is handled as waste material in gypsum ponds. The phosphoric acid is separated from the gypsum and other insolubles by vacuum filtration. The acid is then normally concentrated to about 50 to 55 percent P_2O_5. When superphosphoric acid is made, the acid is concentrated to between 70 and 85 percent P_2O_5.

Emissions of gaseous fluorides, consisting mostly of silicon tetrafluoride and hydrogen fluoride, are the major problems from wet-process acid. Table 5.11-1 summarizes the emission factors from both wet-process acid and thermal-process acid.

5.11.2 Thermal Process[1]

In the thermal process, phosphate rock, siliceous flux, and coke are heated in an electric furnace to produce elemental phosphorus. The gases containing the phosphorus vapors are passed through an electrical precipitator to remove entrained dust. In the "one-step" version of the process, the gases are next mixed with air to form P_2O_5 before passing to a water scrubber to form phosphoric acid. In the "two-step" version of the process, the phosphorus is condensed and pumped to a tower in which it is burned with air, and the P_2O_5 formed is hydrated by a water spray in the lower portion of the tower.

The principal emission from thermal-process acid is P_2O_5 acid mist from the absorber tail gas. Since all plants are equipped with some type of acid-mist collection system, the emission factors presented in Table 5.11-1 are based on the listed types of control.

Table 5.11-1. EMISSION FACTORS FOR PHOSPHORIC ACID PRODUCTION
EMISSION FACTOR RATING: B

Source	Particulates		Fluorides	
	lb/ton	kg/MT	lb/ton	kg/MT
Wet process (phosphate rock)				
Reactor, uncontrolled			18[a]	9[a]
Gypsum pond			1[b]	1.1[b]
Condenser, uncontrolled			20[a]	10[a]
Thermal process (phosphorus burned[c])				
Packed tower	4.6	2.3		
Venturi scrubber	5.6	2.8		
Glass fiber mist eliminator	3.0	1.5		
Wire mesh mist eliminator	2.7	1.36		
High pressure drop mist eliminator	0.2	0.1		
Electrostatic precipitator	1.8	0.9		

[a] References 2 and 3.

[b] Pounds per acre per day (kg/hectare-day); approximately 0.5 acre (0.213 hectare) is required to produce 1 ton of P_2O_5 daily.

[c] Reference 4.

References for Section 5.11

1. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 16.

2. Atmospheric Emissions from Wet-Process Phosphoric Acid Manufacture. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration. Raleigh, N.C. Publication Number AP-57. April 1970.

3. Control Techniques for Fluoride Emissions. Internal document. U.S. EPA, Office of Air Programs. Research Triangle Park, N.C. 1970.

4. Atmospheric Emissions from Thermal-Process Phosphoric Acid Manufacturing. Cooperative Study Project: Manufacturing Chemists' Association, Incorporated, and Public Health Service. U.S. DHEW, PHS, National Air Pollution Control Administration. Durham, N.C. Publication Number AP-48. October 1968.

5.12 PHTHALIC ANHYDRIDE

5.12.1 Process Description[1,2]

Phthalic anhydride is produced primarily by oxidizing naphthalene vapors with excess air over a catalyst, usually V_2O_5. O-xylene can be used instead of naphthalene, but it is not used as much. Following the oxidation of the naphthalene vapors, the gas stream is cooled to separate the phthalic vapor from the effluent. Phthalic anhydride crystallizes directly from this cooling without going through the liquid phase. The phthalic anhydride is then purified by a chemical soak in sulfuric acid, caustic, or alkali metal salt, followed by a heat soak. To produce 1 ton of phthalic anhydride, 2,300 pounds of naphthalene and 800,000 standard cubic feet (scf) of air are required (i.e., 1,150 kilograms of naphthalene and 25,000 standard cubic meters of air to produce 1 MT of phthalic anhydride).

5.12.2 Emissions and Controls[1]

The excess air from the production of phthalic anhydride contains some uncondensed phthalic anhydride, maleic anhydride, quinones, and other organics. The venting of this stream to the atmosphere is the major source of organic emissions. These emissions can be controlled with catalytic combustion. Table 5.12-1 presents emission factor data from phthalic anhydride plants.

Table 5.12-1. EMISSION FACTORS FOR PHTHALIC ANHYDRIDE PLANTS[a]
EMISSION FACTOR RATING: E

Overall plant	Organics (as hexane)	
	lb/ton	kg/MT
Uncontrolled	32	16
Following catalytic combustion	11	5.5

[a] Reference 3.

References for Section 5.12

1. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 37.

2. Phthalic Anhydride. Kirk-Othmer Encyclopedia of Chemical Technology. Vol. 15, 2nd Ed. New York, John Wiley and Sons, Inc. p. 444-455. 1968.

3. Rolke, R.W., et al. Afterburner Source Test Procedure for the Evaluation of Industrial Fume Converters. (Presented at 58th Annual Meeting of the Air Pollution Control Association. Toronto, Canada. June 1965.)

5.13 PLASTICS

5.13.1 Process Description[1]

The manufacture of most resins or plastics begins with the polymerization or linking of the basic compound (monomer), usually a gas or liquid, into high molecular weight noncrystalline solids. The manufacture of the basic monomer is not considered part of the plastics industry and is usually accomplished at a chemical or petroleum plant.

The manufacture of most plastics involves an enclosed reaction or polymerization step, a drying step, and a final treating and forming step. These plastics are polymerized or otherwise combined in completely enclosed stainless steel or glass-lined vessels. Treatment of the resin after polymerization varies with the proposed use. Resins for moldings are dried and crushed or ground into molding powder. Resins such as the alkyd resins that are to be used for protective coatings are normally transferred to an agitated thinning tank, where they are thinned with some type of solvent and then stored in large steel tanks equipped with water-cooled condensers to prevent loss of solvent to the atmosphere. Still other resins are stored in latex form as they come from the kettle.

5.13.2 Emissions and Controls[1]

The major sources of air contamination in plastics manufacturing are the emissions of raw materials or monomers, emissions of solvents or other volatile liquids during the reaction, emissions of sublimed solids such as phthalic anhydride in alkyd production, and emissions of solvents during storage and handling of thinned resins. Emission factors for the manufacture of plastics are shown in Table 5.13-1.

Table 5.13-1. EMISSION FACTORS FOR PLASTICS
MANUFACTURING WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: E

Type of plastic	Particulate		Gases	
	lb/ton	kg/MT	lb/ton	kg/MT
Polyvinyl chloride	35[b]	17.5[b]	17[c]	8.5[c]
Polypropylene	3	1.5	0.7[d]	0.35[d]
General	5 to 10	2.5 to 5		

[a] References 2 and 3.

[b] Usually controlled with fabric filter efficiency of 98 to 99 percent.

[c] As vinyl chloride.

[d] As propylene.

Much of the control equipment used in this industry is a basic part of the system and serves to recover a reactant or product. These controls include floating roof tanks or vapor recovery systems on volatile material storage units, vapor recovery systems (adsorption or condensers), purge lines that vent to a flare system, and recovery systems on vacuum exhaust lines.

References for Section 5.13

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Unpublished data from industrial questionnaire. U.S. DHEW, PHS, National Air Pollution Control Administration, Division of Air Quality and Emissions Data. Durham, N.C. 1969.

3. Private Communication between Resources Research, Incorporated, and Maryland State Department of Health, Baltimore, Md. November 1969.

5.14 PRINTING INK

5.14.1 Process Description[1]

There are four major classes of printing ink: letterpress and lithographic inks, commonly called oil or paste inks; and flexographic and rotogravure inks, which are referred to as solvent inks. These inks vary considerably in physical appearance, composition, method of application, and drying mechanism. Flexographic and rotogravure inks have many elements in common with the paste inks but differ in that they are of very low viscosity, and they almost always dry by evaporation of highly volatile solvents.[2]

There are three general processes in the manufacture of printing inks: (1) cooking the vehicle and adding dyes, (2) grinding of a pigment into the vehicle using a roller mill, and (3) replacing water in the wet pigment pulp by an ink vehicle (commonly known as the flushing process).[3] The ink "varnish" or vehicle is generally cooked in large kettles at 200° to 600°F (93° to 315°C) for an average of 8 to 12 hours in much the same way that regular varnish is made. Mixing of the pigment and vehicle is done in dough mixers or in large agitated tanks. Grinding is most often carried out in three-roller or five-roller horizontal or vertical mills.

5.14.2 Emissions and Controls[1,3]

Varnish or vehicle preparation by heating is by far the largest source of ink manufacturing emissions. Cooking the varnish components — resins, drying oils, petroleum oils, and solvents — produces odorous emissions. At about 350°F (175°C) the products begin to decompose, resulting in the emission of decomposition products from the cooking vessel. Emissions continue throughout the cooking process with the maximum rate of emissions occurring just after the maximum temperature has been reached. Emissions from the cooking phase can be reduced by more than 90 percent with the use of scrubbers or condensers followed by afterburners.[4,5]

Compounds emitted from the cooking of oleoresinous varnish (resin plus varnish) include water vapor, fatty acids, glycerine, acrolein, phenols, aldehydes, ketones, terpene oils, terpenes, and carbon dioxide. Emissions of thinning solvents used in flexographic and rotogravure inks may also occur.

The quantity, composition, and rate of emissions from ink manufacturing depend upon the cooking temperature and time, the ingredients, the method of introducing additives, the degree of stirring, and the extent of air or inert gas blowing. Particulate emissions resulting from the addition of pigments to the vehicle are affected by the type of pigment and its particle size. Emission factors for the manufacture of printing ink are presented in Table 5.14-1.

Table 5.14-1. EMISSION FACTORS FOR PRINTING INK MANUFACTURING[a]
EMISSION FACTOR RATING: E

Type of process	Gaseous organic[b] lb/ton of product	Gaseous organic[b] kg/MT of product	Particulates lb/ton of pigment	Particulates kg/MT of pigment
Vehicle cooking				
General	120	60	–	–
Oils	40	20	–	–
Oleoresinous	150	75	–	–
Alkyds	160	80	–	–
Pigment mixing			2	1

[a] Based on data from section on paint and varnish.
[b] Emitted as gas, but rapidly condense as the effluent is cooled.

References for Section 5.14

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc., Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R. N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Co. 1967. p. 454-455.

3. Larsen, L.M. Industrial Printing Inks. New York, Reinhold Publishing Company. 1962.

4. Chatfield, H.E. Varnish Cookers. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS. National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 688-695.

5. Private communication with Interchemical Corporation, Ink Division. Cincinnati, Ohio. November 10, 1969.

5.15 SOAP AND DETERGENTS

5.15.1 Soap Manufacture[1]

The manufacture of soap entails the catalytic hydrolysis of various fatty acids with sodium or potassium hydroxide to form a glycerol-soap mixture. This mixture is separated by distillation, then neutralized and blended to produce soap. The main atmospheric pollution problem in the manufacture of soap is odor, and, if a spray drier is used, a particulate emission problem may also occur. Vent lines, vacuum exhausts, product and raw material storage, and waste streams are all potential odor sources. Control of these odors may be achieved by scrubbing all exhaust fumes and, if necessary, incinerating the remaining compounds. Odors emanating from the spray drier may be controlled by scrubbing with an acid solution.

5.15.2 Detergent Manufacture[1]

The manufacture of detergents generally begins with the sulfuration by sulfuric acid of a fatty alcohol or linear alkylate. The sulfurated compound is then neutralized with caustic solution (NaOH), and various dyes, perfumes, and other compounds are added.[2,3] The resulting paste or slurry is then sprayed under pressure into a vertical drying tower where it is dried with a stream of hot air (400° to 500°F or 204° to 260°C). The dried detergent is then cooled and packaged. The main source of particulate emissions is the spray-drying tower. Odors may also be emitted from the spray-drying operation and from storage and mixing tanks. Particulate emissions from spray-drying operations are shown in Table 5.15-1.

Table 5.15-1. PARTICULATE EMISSION FACTORS FOR SPRAY-DRYING DETERGENTS[a]
EMISSION FACTOR RATING: B

Control device	Overall efficiency, %	Particulate emissions lb/ton of product	Particulate emissions kg/MT of product
Uncontrolled	-	90	45
Cyclone[b]	85	14	7
Cyclone followed by:			
Spray chamber	92	7	3.5
Packed scrubber	95	5	2.5
Venturi scrubber	97	3	1.5

[a] Based on analysis of data in References 2 through 6.

[b] Some type of primary collector, such as a cyclone, is considered an integral part of the spray-drying system.

References for Section 5.15

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Phelps, A.H. Air Pollution Aspects of Soap and Detergent Manufacture. J. Air Pol. Control Assoc. *17*(8):505-507, August 1967.

3. Shreve, R.N. Chemical Process Industries. 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 544-563.

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5. McCormick, P.Y., R.L. Lucas, and D.R. Wells. Gas-Solid Systems. In: Chemical Engineer's Handbook. Perry, J.H. (ed.). New York, McGraw-Hill Book Company. 1963. p. 59.

6. Private communication with Maryland State Department of Health, Baltimore, Md. November 1969.

5.16 SODIUM CARBONATE (Soda Ash)

5.16.1 Process Description[1]

Soda ash is manufactured by three processes: (1) the natural or Lake Brine process, (2) the Solvay process (ammonia-soda), and (3) the electrolytic soda-ash process. Because the Solvay process accounts for over 80 percent of the total production of soda ash, it will be the only one discussed in this section.

In the Solvay process, the basic raw materials are ammonia, coke, limestone (calcium carbonate), and salt (sodium chloride). The salt, usually in the impurified form of a brine, is first purified in a series of absorbers by precipitation of the heavy metal ions with ammonia and carbon dioxide. In this process sodium bicarbonate is formed. This bicarbonate coke is heated in a rotary kiln, and the resultant soda ash is cooled and conveyed to storage.

5.16.2 Emissions

The major source of emissions from the manufacture of soda ash is the release of ammonia. Small amounts of ammonia are emitted in the gases vented from the brine purification system. Intermittent losses of ammonia can also occur during the unloading of tank trucks into storage tanks. The major sources of dust emissions include rotary dryers, dry solids handling, and processing of lime. Dust emissions of fine soda ash also occur from conveyor transfer points and air classification systems, as well as during tank-car loading and packaging. Emission factors are summarized in Table 5.16-1.

Table 5.16-1. EMISSION FACTORS FOR SODA-ASH PLANTS WITHOUT CONTROLS
EMISSION FACTOR RATING: D

Type of source	Particulates		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT
Ammonia recovery[a,b]	-	-	7	3.5
Conveying, transferring, loading, etc.[c]	6	3	-	-

[a] Reference 2.
[b] Represents ammonia loss following the recovery system.
[c] Based on data in References 3 through 6.

References for Section 5.16

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 225-230.

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4. Faith, W.L., D.B. Keyes, and R.L. Clark. Industrial Chemicals, 3rd Ed. New York. John Wiley and Sons, Inc. 1965.

5. Kaylor, F.B. Air Pollution Abatement Program of a Chemical Processing Industry. J. Air Pol. Control Assoc. *15*:65-67, February 1965.

5.17 SULFURIC ACID

Revised by William Vatavuk
and Donald Carey

5.17.1 Process Description

All sulfuric acid is made by either the lead chamber or the contact process. Because the contact process accounts for more than 97 percent of the total sulfuric acid production in the United States, it is the only process discussed in this section. Contact plants are generally classified according to the raw materials charged to them: (1) elemental sulfur burning, (2) spent acid and hydrogen sulfide burning, and (3) sulfide ores and smelter gas burning plants. The relative contributions from each type of plant to the total acid production are 68, 18.5, and 13.5 percent, respectively.

All contact processes incorporate three basic operations, each of which corresponds to a distinct chemical reaction. First, the sulfur in the feedstock is burned to sulfur dioxide:

$$\underset{\text{Sulfur}}{S} + \underset{\text{Oxygen}}{O_2} \rightarrow \underset{\substack{\text{Sulfur}\\\text{dioxide}}}{SO_2} \qquad (1)$$

Then, the sulfur dioxide is catalytically oxidized to sulfur trioxide:

$$\underset{\substack{\text{Sulfur}\\\text{dioxide}}}{2SO_2} + \underset{\text{Oxygen}}{O_2} \rightarrow \underset{\substack{\text{Sulfur}\\\text{trioxide}}}{2SO_3} \qquad (2)$$

Finally, the sulfur trioxide is absorbed in a strong, aqueous solution of sulfuric acid:

$$\underset{\substack{\text{Sulfur}\\\text{trioxide}}}{SO_3} + \underset{\text{Water}}{H_2O} \rightarrow \underset{\substack{\text{Sulfuric}\\\text{acid}}}{H_2SO_4} \qquad (3)$$

5.17.1.1 **Elemental Sulfur-Burning Plants**[1,2] - Elemental sulfur, such as Frasch-process sulfur from oil refineries, is melted, settled, or filtered to remove ash and is fed into a combustion chamber. The sulfur is burned in clean air that has been dried by scrubbing with 93 to 99 percent sulfuric acid. The gases from the combustion chamber are cooled and then enter the solid catalyst (vanadium pentoxide) converter. Usually, 95 to 98 percent of the sulfur dioxide from the combustion chamber is converted to sulfur trioxide, with an accompanying large evolution of heat. After being cooled, the converter exit gas enters an absorption tower where the sulfur trioxide is absorbed with 98 to 99 percent sulfuric acid. The sulfur trioxide combines with the water in the acid and forms more sulfuric acid.

If oleum, a solution of uncombined SO_3 in H_2SO_4, is produced, SO_3 from the converter is first passed to an oleum tower that is fed with 98 percent acid from the absorption system. The gases from the oleum tower are then pumped to the absorption column where the residual sulfur trioxide is removed.

A schematic diagram of a contact process sulfuric acid plant that burns elemental sulfur is shown in Figure 5.17-1.

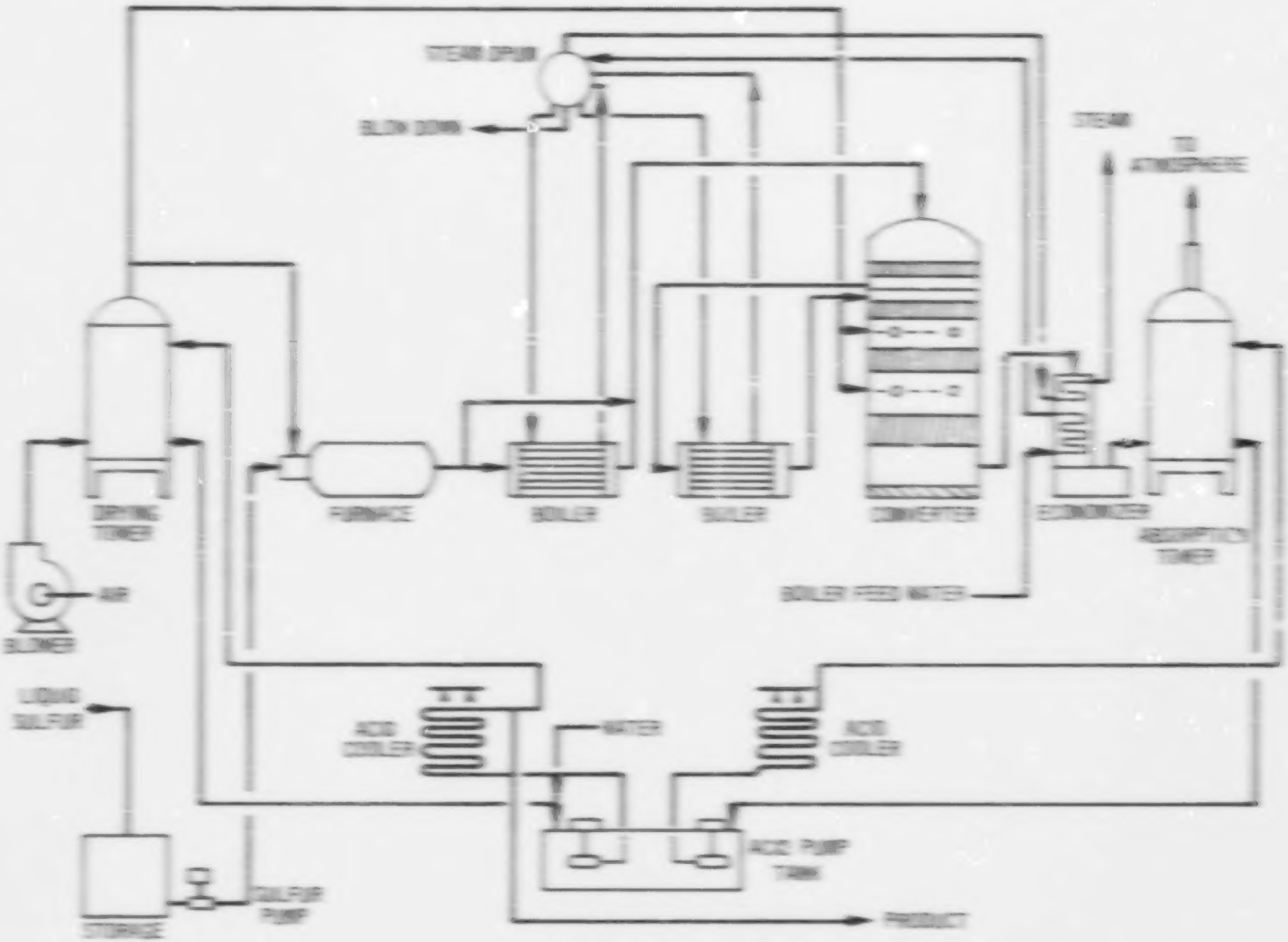
STEAM DRUM
BLOW DOWN
STEAM
TO ATMOSPHERE
DRYING TOWER
AIR
BLOWER
FURNACE
BOILER
BOILER
CONVERTER
ECONOMIZER
ABSORPTION TOWER
BOILER FEED WATER
LIQUID SULFUR
ACID COOLER
WATER
ACID COOLER
ACID PUMP TANK
STORAGE
SULFUR PUMP
PRODUCT

Figure 5.17-1. Basic flow diagram of contact-process sulfuric acid plant burning elemental sulfur.

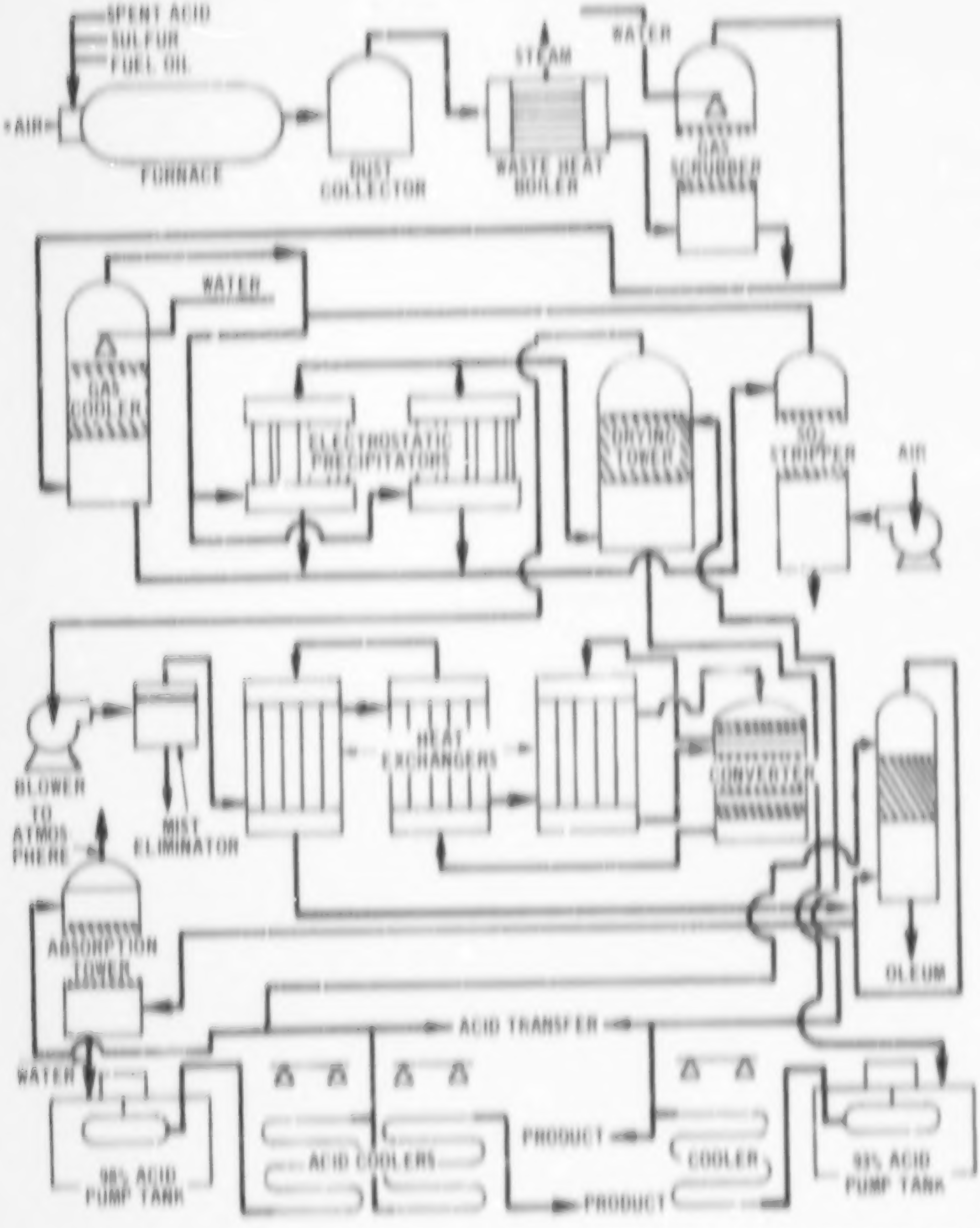
SPENT ACID
SULFUR
FUEL OIL
AIR
FURNACE
DUST COLLECTOR
STEAM
WASTE HEAT BOILER
WATER
GAS SCRUBBER
WATER
GAS COOLER
ELECTROSTATIC PRECIPITATORS
DRYING TOWER
SO2 STRIPPER
AIR
BLOWER
MIST ELIMINATOR
HEAT EXCHANGERS
CONVERTER
TO ATMOSPHERE
ABSORPTION TOWER
OLEUM
ACID TRANSFER
WATER
98% ACID PUMP TANK
ACID COOLERS
PRODUCT
PRODUCT
COOLER
93% ACID PUMP TANK

Figure 5.17-2. Basic flow diagram of contact-process sulfuric acid plant burning spent acid.

5.17.1.2 Spent Acid and Hydrogen Sulfide Burning Plants[1,2] - Two types of plants are used to process this type of sulfuric acid. In one the sulfur dioxide and other combustion products from the combustion of spent acid and/or hydrogen sulfide with undried atmospheric air are passed through gas-cleaning and mist-removal equipment. The gas stream next passes through a drying tower. A blower draws the gas from the drying tower and discharges the sulfur dioxide gas to the sulfur trioxide converter. A schematic diagram of a contact-process sulfuric acid plant that burns spent acid is shown in Figure 5.17-2.

In a "wet-gas plant," the wet gases from the combustion chamber are charged directly to the converter with no intermediate treatment. The gas from the converter flows to the absorber, through which 93 to 98 percent sulfuric acid is circulating.

5.17.1.3 Sulfide Ores and Smelter Gas Plants - The configuration of this type of plant is essentially the same as that of a spent-acid plant (Figure 5.17-2) with the primary exception that a roaster is used in place of the combustion furnace.

The feed used in these plants is smelter gas, available from such equipment as copper converters, reverberatory furnaces, roasters, and flash smelters. The sulfur dioxide in the gas is contaminated with dust, acid mist, and gaseous impurities. To remove the impurities the gases must be cooled to essentially atmospheric temperature and passed through purification equipment consisting of cyclone dust collectors, electrostatic dust and mist precipitators, and scrubbing and gas-cooling towers. After the gases are cleaned and the excess water vapor is removed, they are scrubbed with 98 percent acid in a drying tower. Beginning with the drying tower stage, these plants are nearly identical to the elemental sulfur plants shown in Figure 5.17-1.

5.17.2 Emissions and Controls

5.17.2.1 Sulfur Dioxide[1,2] - Nearly all sulfur dioxide emissions from sulfuric acid plants are found in the exit gases. Extensive testing has shown that the mass of these SO_2 emissions is an inverse function of the sulfur conversion efficiency (SO_2 oxidized to SO_3). This conversion is, in turn, affected by the number of stages in the catalytic converter, the amount of catalyst used, the temperature and pressure, and the concentrations of the reactants, sulfur dioxide and oxygen. For example, if the inlet SO_2 concentration to the converter were 8 percent by volume (a representative value), and the conversion temperature were 473°C, the conversion efficiency would be 96 percent. At this conversion, the uncontrolled emission factor for SO_2 would be 55 pounds per ton (27.5 kg/MT) of 100 percent sulfuric acid produced, as shown in Table 5.17-1. For purposes of comparison, note that the Environmental Protection Agency performance standard[3] for new and modified plants is 4 pounds per ton (2kg/MT) of 100 percent acid produced, maximum 2-hour average. As Table 5.17-1 and Figure 5.17-3 indicate, achieving this standard requires a conversion efficiency of 99.7 percent in an uncontrolled plant or the equivalent SO_2 collection mechanism in a controlled facility. Most single absorption plants have SO_2 conversion efficiencies ranging from 95 to 98 percent.

In addition to exit gases, small quantities of sulfur oxides are emitted from storage tank vents and tank car and tank truck vents during loading operations; from sulfuric acid concentrators; and through leaks in process equipment. Few data are available on emissions from these sources.

Of the many chemical and physical means for removing SO_2 from gas streams, only the dual absorption and the sodium sulfite-bisulfite scrubbing processes have been found to increase acid production without yielding unwanted by-products.

Table 5.17-1. EMISSION FACTORS FOR SULFURIC ACID PLANTS[a]
EMISSION FACTOR RATING: A

Conversion of SO_2 to SO_3, %	SO_2 emissions	
	lb/ton of 100% H_2SO_4	kg/MT of 100% H_2SO_4
93	96	48.0
94	82	41.0
95	70	35.0
96	55	27.5
97	40	20.0
98	27	13.0
99	14	7.0
99.5	7	3.5
99.7	4	2.0
100[b]	0	0.0

[a] Reference 1.

[b] The following linear interpolation formula can be used for calculating emission factors for conversion efficiencies between 93 and 100 percent: emission factor (lb/ton acid) = -13.65 (percent conversion efficiency) + 1365.

In the dual absorption process, the SO_3 gas formed in the primary converter stages is sent to a primary absorption tower where H_2SO_4 is formed. The remaining unconverted sulfur dioxide is forwarded to the final stages in the converter, from whence it is sent to the secondary absorber for final sulfur trioxide removal. The result is the conversion of a much higher fraction of SO_2 to SO_3 (a conversion of 99.7 percent or higher, on the average, which meets the performance standard). Furthermore, dual absorption permits higher converter inlet sulfur dioxide concentrations than are used in single absorption plants because the secondary conversion stages effectively remove any residual sulfur dioxide from the primary absorber.

Where dual absorption reduces sulfur dioxide emissions by increasing the overall conversion efficiency, the sodium sulfite-bisulfite scrubbing process removes sulfur dioxide directly from the absorber exit gases. In one version of this process, the sulfur dioxide in the waste gas is absorbed in a sodium sulfite solution, separated, and recycled to the plant. Test results from a 750 ton (680 MT) per day plant equipped with a sulfite scrubbing system indicated an average emission factor of 2.7 pounds per ton (1.35 kg/MT).

5.17.2.3 Acid Mist[1,3] - Nearly all the acid mist emitted from sulfuric acid manufacturing can be traced to the absorber exit gases. Acid mist is created when sulfur trioxide combines with water vapor at a temperature below the dew point of sulfur trioxide. Once formed within the process system, this mist is so stable that only a small quantity can be removed in the absorber.

In general, the quantity and particle size distribution of acid mist are dependent on the type of sulfur feedstock used, the strength of acid produced, and the conditions in the absorber. Because it contains virtually no water vapor, bright elemental sulfur produces little acid mist when burned; however, the hydrocarbon impurities in other feedstocks — dark sulfur, spent acid, and hydrogen sulfide — oxidize to water vapor during combustion. The water vapor, in turn, combines with sulfur trioxide as the gas cools in the system.

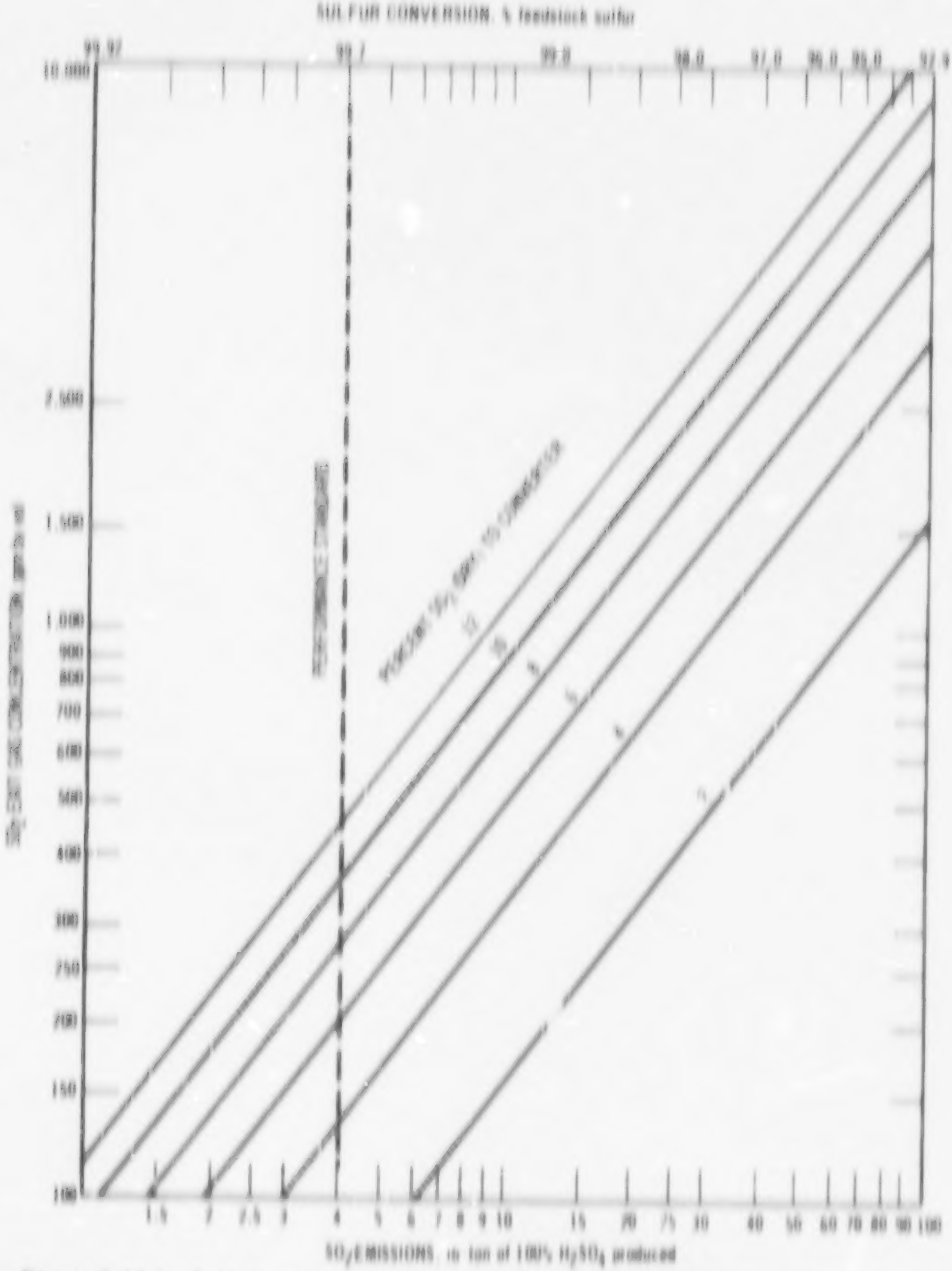

Figure 5.17-3. Sulfuric acid plant feedstock sulfur conversion versus volumetric and mass SO_2 emissions at various inlet SO_2 concentrations by volume.

The strength of acid produced—whether oleum or 99 percent sulfuric acid—also affects mist emissions. Oleum plants produce greater quantities of finer, more stable mist. For example, uncontrolled mist emissions from oleum plants burning spent acid range from 0.1 to 10.0 pounds per ton (0.05 to 5.0 kg/MT), while those from 98 percent acid plants burning elemental sulfur range from 0.4 to 4.0 pounds per ton (0.2 to 2.0 kg/MT). Furthermore, 85 to 95 weight percent of the mist particles from oleum plants are less than 2 microns in diameter, compared with only 30 weight percent that are less than 2 microns in diameter from 98 percent acid plants.

The operating temperature of the absorption column directly affects sulfur trioxide absorption and, accordingly, the quality of acid mist formed after exit gases leave the stack. The optimum absorber operating temperature is dependent on the strength of the acid produced, throughput rates, inlet sulfur trioxide concentrations, and other variables peculiar to each individual plant. Finally, it should be emphasized that the percentage conversion of sulfur dioxide to sulfur trioxide has no direct effect on acid mist emissions. In Table 5.17-2 uncontrolled acid mist emissions are presented for various sulfuric acid plants.

Two basic types of devices, electrostatic precipitators and fiber mist eliminators, effectively reduce the acid mist concentration from contact plants to less than the EPA new source performance standard, which is 0.15 pound per ton (0.075 kg/MT) of acid. Precipitators, if properly maintained, are effective in collecting the mist particles at efficiencies up to 99 percent (see Table 5.17-3).

The three most commonly used fiber mist eliminators are the vertical tube, vertical panel, and horizontal dual-pad types. They differ from one another in the arrangement of the fiber elements, which are composed of either chemically resistant glass or fluorocarbon, and in the means employed to collect the trapped liquid. The operating characteristics of these three types are compared with electrostatic precipitators in Table 5.17-3.

Table 5.17-2. ACID MIST EMISSION FACTORS FOR SULFURIC ACID PLANTS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: B

Raw material	Oleum produced, % total output	Emissions[b] lb/ton acid	kg/MT acid
Recovered sulfur	0 to 43	0.35 to 0.8	0.175 to 0.4
Bright virgin sulfur	0	1.7	0.85
Dark virgin sulfur	33 to 100	0.32 to 6.3	0.16 to 3.15
Sulfide ores	0 to 25	1.2 to 7.4	0.6 to 3.7
Spent acid	0 to 77	2.2 to 2.7	1.1 to 1.35

[a] Reference 1.

[b] Emissions are proportional to the percentage of oleum in the total product. Use the low end of ranges for low oleum percentage and high end of ranges for high oleum percentage.

Table 5.17-3. EMISSION COMPARISON AND COLLECTION EFFICIENCY OF TYPICAL ELECTROSTATIC PRECIPITATOR AND FIBER MIST ELIMINATORS[a]

Control device	Particle size collection efficiency, %		Acid mist emissions			
			98% acid plants[b]		oleum plants	
	>3 µm	<3 µm	lb/ton	kg/MT	lb/ton	kg/MT
Electrostatic precipitator	99	100	0.10	0.05	0.12	0.06
Fiber mist eliminator						
Tubular	100	95 to 99	0.02	0.01	0.02	0.01
Panel	100	90 to 98	0.10	0.05	0.10	0.05
Dual pad	100	93 to 99	0.11	0.055	0.11	0.055

[a] Reference 2.

[b] Based on manufacturers' generally expected results; calculated for 8 percent sulfur dioxide concentration in gas converter.

References for Section 5.17

1. Atmospheric Emissions from Sulfuric Acid Manufacturing Processes. U.S. DHEW, PHS, National Air Pollution Control Administration. Washington, D.C. Publication Number 999-AP-13. 1966.

2. Unpublished report on control of air pollution from sulfuric acid plants. Environmental Protection Agency. Research Triangle Park, N.C. August 1971.

3. Standards of Performance for New Stationary Sources. Environmental Protection Agency. Washington, D.C. Federal Register. 36(247): December 23, 1971.

5.18 SULFUR

By William Vatavuk

5.18.1 Process Description

Nearly all of the elemental sulfur produced from hydrogen sulfide is made by the modified Claus process. The process (Figure 5.18-1) consists of the multistage oxidation of hydrogen sulfide according to the following reaction:

$$\underset{\text{Hydrogen sulfide}}{2H_2S} + \underset{\text{Oxygen}}{O_2} \longrightarrow \underset{\text{Sulfur}}{2S} + \underset{\text{Water}}{2H_2O}$$

In the first step, approximately one third of the hydrogen sulfide is reacted with air in a pressurized boiler (1.0 to 1.5 atmospheres) where most of the heat of reaction and some of the sulfur are removed. After removal of the water vapor and sulfur, the cooled gases are heated to between 400 and 500°F, and passed over a "Claus" catalyst bed composed of bauxite or alumina, where the reaction is completed. The degree of reaction completion is a function of the number of catalytic stages employed. Two stages can recover 92 to 95 percent of the potential sulfur; three stages, 95 to 96 percent; and four stages, 96 to 97 percent. The conversion to sulfur is ultimately limited by the reverse reaction in which water vapor recombines with sulfur to form gaseous hydrogen sulfide and sulfur dioxide. Additional amounts of sulfur are lost as vapor, entrained mist, or droplets and as carbonyl sulfide and carbon disulfide (0.25 to 2.5 percent of the sulfur fed). The latter two compounds are formed in the pressurized boiler at high temperature (1500 to 2500°F) in the presence of carbon compounds.

The plant tail gas, containing the above impurities in volume quantities of 1 to 3 percent, usually passes to an incinerator, where all of the sulfur is oxidized to sulfur dioxide at temperatures ranging from 1000 to 1200°F. The tail gas containing the sulfur dioxide then passes to the atmosphere via a stack.

5.18.2 Emissions and Controls[1-3]

Virtually all of the emissions from sulfur plants consist of sulfur dioxide, the main incineration product. The quantity of sulfur dioxide emitted is, in turn, a function of the number of conversion stages employed, the process temperature and pressure, and the amounts of carbon compounds present in the pressurized boiler.

The most commonly used control method involves two main steps -- conversion of sulfur dioxide to hydrogen sulfide followed by the conversion of hydrogen sulfide to elemental sulfur. Conversion of sulfur dioxide to hydrogen sulfide occurs via catalytic hydrogenation or hydrolysis at temperatures from 600 to 700°F. The products are cooled to remove the water vapor and then reacted with a sodium carbonate solution to yield sodium hydrosulfide. The hydrosulfide is oxidized to sulfur in solution by sodium vanadate. Finely divided sulfur appears as a froth that is skimmed off, washed, dried by centrifugation, and added to the plant product. Overall recovery of sulfur approaches 100 percent if this process is employed. Table 5.18-1 lists emissions from controlled and uncontrolled sulfur plants.

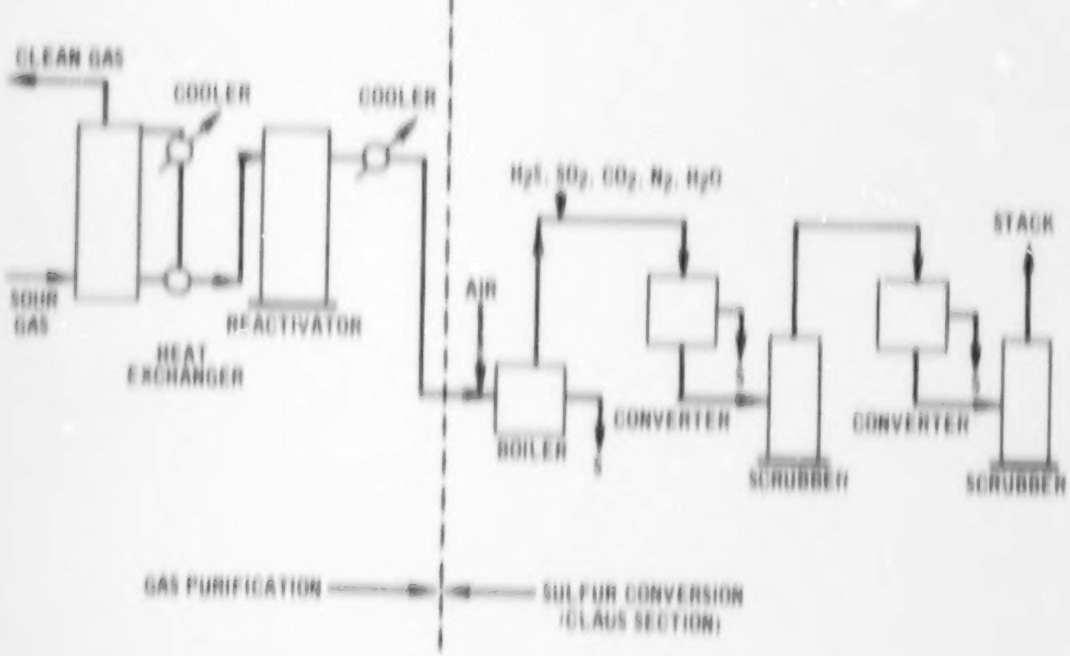
CLEAN GAS
COOLER
COOLER
H_2S, SO_2, CO_2, N_2, H_2O
STACK
AIR
SOUR GAS
REACTIVATOR
HEAT EXCHANGER
S
CONVERTER
BOILER
S
SCRUBBER
CONVERTER
S
SCRUBBER
GAS PURIFICATION
SULFUR CONVERSION (CLAUS SECTION)

Figure 5.18-1. Basic flow diagram of modified Claus process with two converter stages used in manufacturing sulfur.

Table 5.18-1. EMISSION FACTORS FOR MODIFIED CLAUS SULFUR PLANTS EMISSION FACTOR RATING: D

Number of catalytic stages	Recovery of of sulfur, %	SO_2 emissions[a]	
		lb/ton 100% sulfur	kg/MT 100% sulfur
Two, uncontrolled	92 to 95	211 to 348	106 to 162
Three, uncontrolled	95 to 96	167 to 211	84 to 106
Four, uncontrolled	96 to 97	124 to 167	62 to 84
Sulfur removal process	99.9	4.0	2.0

[a] The range in emission factors corresponds to the range in the percentage recovery of sulfur.

References for Section 5.18

1. Beavon, David K. Abating Sulfur Plant Tail Gases. Pollution Engineering. 4(1):34-35, January 1972.

2. Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 19. New York, John Wiley and Sons, Inc. 1969.

5.19 SYNTHETIC FIBERS

5.19.1 Process Description[1]

Synthetic fibers are classified into two major categories, semi-synthetic and "true" synthetic. Semi-synthetics, such as viscose rayon and acetate fibers, result when natural polymeric materials such as cellulose are brought into a dissolved or dispersed state and then spun into fine filaments. True synthetic polymers, such as Nylon,* Orlon, and Dacron, result from addition and other polymerization reactions that form long chain molecules.

True synthetic fibers begin with the preparation of extremely long, chain-like molecules. The polymer is spun in one of four ways:[2] (1) melt spinning, in which molten polymer is pumped through spinneret jets, the polymer solidifying as it strikes the cool air; (2) dry spinning, in which the polymer is dissolved in a suitable organic solvent, and the resulting solution is forced through spinnerets; (3) wet spinning, in which the solution is coagulated in a chemical as it emerges from the spinneret; and (4) core spinning, the newest method, in which a continuous filament yarn together with short-length "hard" fibers is introduced onto a spinning frame in such a way as to form a composite yarn.

5.19.2 Emissions and Controls[1]

In the manufacture of viscose rayon, carbon disulfide and hydrogen sulfide are the major gaseous emissions. Air pollution controls are not normally used to reduce these emissions, but adsorption in activated carbon at an efficiency of 80 to 95 percent, with subsequent recovery of the CS_2 can be accomplished.[3] Emissions of gaseous hydrocarbons may also occur from the drying of the finished fiber. Table 5.19-1 presents emission factors for semi-synthetic and true synthetic fibers.

Table 5.19-1. EMISSION FACTORS FOR SYNTHETIC FIBERS MANUFACTURING
EMISSION FACTOR RATING: E

Type of fiber	Hydrocarbons		Carbon disulfide		Hydrogen sulfide		Oil vapor or mist	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Semi-synthetic								
Viscose rayon[a,b]	-	-	55	27.5	6	3	-	-
True synthetic[c]								
Nylon	7	3.5	-	-	-	-	15	7.5
Dacron	-	-	-	-	-	-	7	3.5

[a] Reference 4.

[b] May be reduced by 80 to 95 percent adsorption in activated charcoal.[3]

[c] Reference 5.

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*Mention of company or product names does not constitute endorsement by the Environmental Protection Agency.

References for Section 5.19

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration. Durham, N.C., under Contract Number CPA 22-69-119. April 1970.

2. Fibers, Man-Made. In: Kirk-Othmer Encyclopedia of Chemical Technology. New York, John Wiley and Sons, Inc. 1969.

3. Fluidized Recovery System Nabs Carbon Disulfide. Chem. Eng. 70(8):92-94, April 15, 1963.

4. Private communication between Resources Research, Incorporated, and Rayon Manufacturing Plant. December 1969.

5. Private communication between Resources Research, Incorporated, and E.I. Dupont de Nemours and Company. January 13, 1970.

5.20 SYNTHETIC RUBBER

5.20.1 Process Description[1]

Copolymers of butadiene and styrene, commonly known as SBR, account for more than 70 percent of all synthetic rubber produced in the United States. In a typical SBR manufacturing process, the monomers of butadiene and styrene are mixed with additives such as soaps and mercaptans. The mixture is polymerized to a conversion point of approximately 60 percent. After being mixed with various ingredients such as oil and carbon black, the latex product is coagulated and precipitated from the latex emulsion. The rubber particles are then dried and baled.

5.20.2 Emissions and Controls[1]

Emissions from the synthetic rubber manufacturing process consist of organic compounds (largely the monomers used) emitted from the reactor and blow-down tanks, and particulate matter and odors from the drying operations.

Drying operations are frequently controlled with fabric filter systems to recover any particulate emissions, which represent a product loss. Potential gaseous emissions are largely controlled by recycling the gas stream back to the process. Emission factors from synthetic rubber plants are summarized in Table 5.20-1.

Table 5.20-1. EMISSION FACTORS FOR SYNTHETIC RUBBER PLANTS: BUTADIENE-ACRYLONITRILE AND BUTADIENE-STYRENE
EMISSION FACTOR RATING: E

Compound	Emissions[a, b]	
	lb/ton	kg/MT
Alkenes		
Butadiene	40	20
Methyl propene	15	7.5
Butyne	3	1.5
Pentadiene	1	0.5
Alkanes		
Dimethylheptane	1	0.5
Pentane	2	1
Ethanenitrile	1	0.5
Carbonyls		
Acrylonitrile	17	8.5
Acrolein	3	1.5

[a] The butadiene emission is not continuous and is greatest right after a batch of partially polymerized latex enters the blow-down tank.
[b] References 2 and 3.

References for Section 5.20

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. The Louisville Air Pollution Study. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. 1961. p. 26-27 and 124.

3. Unpublished data from synthetic rubber plant. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration, Division of Air Quality and Emissions Data. Durham, N.C. 1969.

5.21 TEREPHTHALIC ACID

5.21.1 Process Description[1,2]

The main use of terephthalic acid is to produce dimethylterephthalate, which is used for polyester fibers (like Dacron) and films. Terephthalic acid can be produced in various ways, one of which is the oxidation of *p*-xylene by nitric acid. In this process an oxygen-containing gas (usually air), *p*-xylene, and HNO_3 are all passed into a reactor where oxidation by the nitric acid takes place in two steps. The first step yields primarily N_2O; the second step yields mostly NO in the offgas. The terephthalic acid precipitated from the reactor effluent is recovered by conventional crystallization, separation, and drying operations.

5.21.2 Emissions

The NO in the offgas from the reactor is the major air contaminant from the manufacture of terephthalic acid. The amount of nitrogen oxides emitted is roughly estimated in Table 5.21-1.

Table 5.21-1. NITROGEN OXIDES EMISSION FACTORS FOR TEREPHTHALIC ACID PLANTS[a]
EMISSION FACTOR RATING: D

	Nitrogen oxides (NO)	
Type of operation	lb/ton	kg/MT
Reactor	13	6.5

[a] Reference 2.

References for Section 5.21

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C. under Contract Number CPA-22-69-119. April 1970.

2. Terephthalic Acid. In: Kirk-Othmer Encyclopedia of Chemical Technology. Vol. 9. New York, John Wiley and Sons, Inc. 1964.

6. FOOD AND AGRICULTURAL INDUSTRY

Before food and agricultural products are used by the consumer they undergo a number of processing steps, such as refinement, preservation, and product improvement, as well as storage and handling, packaging, and shipping. This section deals with the processing of food and agricultural products and the intermediate steps that present air pollution problems. Emission factors are presented for industries where data were available. The primary pollutant emitted from these processes is particulate matter.

6.1 ALFALFA DEHYDRATING

6.1.1 General[1,2]

An alfalfa dehydrating plant produces an animal feed from alfalfa. The dehydration and grinding of alfalfa that produces alfalfa meal is a dusty operation most commonly carried out in rural areas.

Wet, chopped alfalfa is fed into a direct fired rotary drier. The dried alfalfa particles are conveyed to a primary cyclone and sometimes a secondary cyclone in series to settle out the product from air flow and products of combustion. The settled material is discharged to the grinding equipment, which is usually a hammer mill. The ground material is collected in an air-meal separator and is either conveyed directly to bagging or storage, or blended with other ingredients.

6.1.2 Emissions and Controls

Sources of dust emissions are the primary cyclone, the grinders, and the air-meal separator. Overall dust losses have been reported as high as 7 percent,[2] but average losses are around 3 percent by weight of the meal produced.[3] The use of a baghouse as a secondary collection system can greatly reduce emissions. Emission factors for alfalfa dehydration are presented in Table 6.1-1.

Table 6.1-1. PARTICULATE EMISSION FACTORS FOR ALFALFA DEHYDRATION[a]
EMISSION FACTOR RATING: E

Type of operation	Particulate emissions	
	lb/ton of meal produced	kg/MT of meal produced
Uncontrolled	60	30
Baghouse collector	3	1.5

[a] Reference 3.

References for Section 6.1

1. Duprey, R. L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 19.

2. Stern, A. (ed.). Air Pollution, Volume III. Sources of Air Pollution and Their Control, 2nd Ed. New York, Academic Press. 1968.

3. Process Flow Sheets and Air Pollution Controls. American Conference of Governmental Industrial Hygienists, Committee on Air Pollution. Cincinnati, Ohio. 1961.

6.2 COFFEE ROASTING

6.2.1 Process Description[1,2]

Coffee, which is imported in the form of green beans, must be cleaned, blended, roasted, and packaged before being sold. In a typical coffee roasting operation, the green coffee beans are freed of dust and chaff by dropping the beans into a current of air. The cleaned beans are then sent to a batch or continuous roaster. During the roasting, moisture is driven off, the beans swell, and chemical changes take place that give the roasted beans their typical color and aroma. When the beans have reached a certain color, they are quenched, cooled, and stoned.

6.2.2 Emissions[1,2]

Dust, chaff, coffee bean oils (as mists), smoke, and odors are the principal air contaminants emitted from coffee processing. The major source of particulate emissions and practically the only source of aldehydes, nitrogen oxides, and organic acids is the roasting process. In a direct-fired roaster, gases are vented without recirculation through the flame. In the indirect-fired roaster, however, a portion of the roaster gases are recirculated and particulate emissions are reduced. Emissions of both smoke and odors from the roasters can be almost completely removed by a properly designed afterburner.[1,2]

Particulate emissions also occur from the stoner and cooler. In the stoner, contaminating materials heavier than the roasted beans are separated from the beans by an air stream. In the cooler, quenching the hot roasted beans with water causes emissions of large quantities of steam and some particulate matter.[3] Table 6.2-1 summarizes emissions from the various operations involved in coffee processing.

Table 6.2-1. EMISSION FACTORS FOR ROASTING PROCESSES WITHOUT CONTROLS
EMISSION FACTOR RATING: B

Type of process	Pollutant							
	Particulates[a]		NO_x[b]		Aldehydes[b]		Organic acids[b]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Roaster:								
Direct fired	7.6	3.8	0.1	0.05	0.2	0.1	0.9	0.45
Indirect fired	4.2	2.1	0.1	0.05	0.2	0.1	0.9	0.45
Stoner and cooler[c]	1.4	0.7	–	–	–	–	–	–
Instant coffee spray dryer	1.4[d]	0.7[d]	–	–	–	–	–	–

[a] Reference 3.
[b] Reference 1.
[c] If cyclone is used, emissions can be reduced by 70 percent.
[d] Cyclone plus wet scrubber always used, representing a controlled factor.

References for Section 6.2

1. Polglase, W.L., H.F. Dey, and R.T. Walsh. Coffee Processing. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 746-749.

2. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 19-20.

3. Partee, F. Air Pollution in the Coffee Roasting Industry. Revised Ed. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. Publication Number 999-AP-9. 1966.

6.3 COTTON GINNING

6.3.1 General[1]

The primary function of a cotton gin is to take raw seed cotton and separate the seed and the lint. A large amount of trash is found in the seed cotton, and it must also be removed. The problem of collecting and disposing of gin trash is two-fold. The first problem consists of collecting the coarse, heavier trash such as burrs, sticks, stems, leaves, sand, and dirt. The second problem consists of collecting the finer dust, small leaf particles, and fly lint that are discharged from the lint after the fibers are removed from the seed. From 1 ton (0.907 MT) of seed cotton, approximately one 500-pound (226-kilogram) bale of cotton can be made.

6.3.2 Emissions and Controls

The major sources of particulates from cotton ginning include the unloading fan, the cleaner, and the stick and burr machine. From the cleaner and stick and burr machine, a large percentage of the particles settle out in the plant, and an attempt has been made in Table 6.3-1 to present emission factors that take this into consideration. Where cyclone collectors are used, emissions have been reported to be about 90 percent less.[1]

Table 6.3-1. EMISSION FACTORS FOR COTTON GINNING OPERATIONS WITHOUT CONTROLS[a,b]
EMISSION FACTOR RATING: C

Process	Estimated total particulates		Particles > 100 µm settled out, %	Estimated emission factor (released to atmosphere)	
	lb/bale	kg/bale		lb/bale	kg/bale
Unloading fan	5	2.27	0	5.0	2.27
Cleaner	1	0.45	70	0.30	0.14
Stick and burr machine	3	1.36	95	0.20	0.09
Miscellaneous	3	1.36	50	1.5	0.68
Total	12	5.44	–	7.0	3.2

[a] References 1 and 2.
[b] One bale weighs 500 pounds (226 kilograms).

References for Section 6.3

1. Air-Borne Particulate Emissions from Cotton Ginning Operations. U.S. DHEW, PHS, Taft Sanitary Engineering Center. Cincinnati, Ohio. 1960.

2. Control and Disposal of Cotton Ginning Wastes. A Symposium Sponsored by National Center for Air Pollution Control and Agricultural Research Service, Dallas, Texas. May 1966.

6.4 FEED AND GRAIN MILLS AND ELEVATORS

6.4.1 General[1]

Grain elevators are primarily transfer and storage units and are classified as either the smaller, more numerous country elevators or the larger terminal elevators. At grain elevator locations the following operations can occur: receiving, transfer and storage, cleaning, drying, and milling or grinding. Many of the large terminal elevators also process grain at the same location. The grain processing may include wet and dry milling (cereals), flour milling, oil-seed crushing, and distilling. Feed manufacturing involves the receiving, conditioning (drying, sizing, cleaning), blending, and pelleting of the grains, and their subsequent bagging or bulk loading.

6.4.2 Emissions[1]

Emissions from feed and grain operations may be separated into those occurring at elevators and those occurring at grain processing operations or feed manufacturing operations. Emission factors for these operations are presented in Table 6.4-1. Because dust collection systems are generally applied to most phases of these operations to reduce product and component losses, the selection of the final emission factor should take into consideration the overall efficiency of these control systems.

Emissions from grain elevator operations are dependent on the type of grain, the moisture content of the grain (usually 10 to 30 percent), the amount of foreign material in the grain (usually 5 percent or less), the degree of enclosure at loading and unloading areas, the type of cleaning and conveying, and the amount and type of control used.

Factors affecting emissions from grain processing operations include the type of processing (wet or dry), the amount of grain processed, the amount of cleaning, the degree of drying or heating, the amount of grinding, the temperature of the process, and the degree of control applied to the particulates generated.

Factors affecting emissions from feed manufacturing operations include the type and amount of grain handled, the degree of drying, the amount of liquid blended into the feed, the type of handling (conveyor or pneumatic), and the degree of control.

References for Section 6.4

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119, April 1970. Reston, Virginia.

2. Thimsen, D.J. and P.W. Aften. A Proposed Design for Grain Elevator Dust Collector. J. Air Pol. Control Assoc. *18*(11):738-742, November 1968.

3. Private communication between H. L. Kiser, Grain and Feed Dealers National Association, and Resources Research, Inc., Washington, D.C. September 1969.

Table 6.4-1. PARTICULATE EMISSION FACTORS FOR GRAIN HANDLING AND PROCESSING
EMISSION FACTOR RATING: B

Type of source	Emissions	
	lb/ton	kg/MT
Terminal elevators[a]		
Shipping or receiving	1	0.5
Transferring, conveying, etc.	2	1
Screening and cleaning	5	2.5
Drying	6	3
Country elevators[b]		
Shipping or receiving	5	2.5
Transferring, conveying, etc.	3	1.5
Screening and cleaning	8	4
Drying	7	3.5
Grain processing		
Corn meal[c]	5	2.5
Soybean processing[b]	7	3.5
Barley or wheat cleaner[d]	0.2[e]	0.1[e]
Milo cleaner[f]	0.4[e]	0.2[e]
Barley flour milling[c]	3[e]	1.5[e]
Feed manufacturing		
Barley[f]	3[e]	1.5[e]

[a] References 2 and 3.
[b] Reference 3.
[c] References 3 and 4.
[d] References 5 and 6.
[e] At cyclone exit (only non-ether soluble particulates).
[f] Reference 6.

4. Contribution of Power Plants and Other Sources to Suspended Particulate and Sulfur Dioxide Concentrations in Metropolis, Illinois. U.S. DHEW, PHS, National Air Pollution Control Administration. 1966.

5. Larson, G.P., G.I. Fischer, and W.J. Hamming. Evaluating Sources of Air Pollution. Ind. Eng. Chem. 45:1070-1074. May 1953.

6. Donnelly, W.H. Feed and Grain Mills. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 359.

6.5 FERMENTATION

6.5.1 Process Description[1]

For the purpose of this report only the fermentation industries associated with food will be considered. This includes the production of beer, whiskey, and wine.

The manufacturing process for each of these is similar. The four main brewing production stages and their respective sub-stages are: (1) brewhouse operations, which include (a) malting of the barley, (b) addition of adjuncts (corn, grits, and rice) to barley mash, (c) conversion of starch in barley and adjuncts to maltose sugar by enzymatic processes, (d) separation of wort from grain by straining, and (e) hopping and boiling of the wort; (2) fermentation, which includes (a) cooling of the wort, (b) additional yeast cultures, (c) fermentation for 7 to 10 days, (d) removal of settled yeast, and (e) filtration and carbonation; (3) aging, which lasts from 1 to 2 months under refrigeration; and (4) packaging, which includes (a) bottling-pasteurization, and (b) racking draft beer.

The major differences between beer production and whiskey production are the purification and distillation necessary to obtain distilled liquors and the longer period of aging. The primary difference between wine making and beer making is that grapes are used as the initial raw material in wine rather than grains.

6.5.2 Emissions[1]

Emissions from fermentation processes are nearly all gases and primarily consist of carbon dioxide, hydrogen, oxygen, and water vapor, none of which present an air pollution problem. Emissions of particulates, however, can occur in the handling of the grain for the manufacture of beer and whiskey. Gaseous hydrocarbons are also emitted from the drying of spent grains and yeast in beer and from the whiskey-aging warehouses. No significant emissions have been reported for the production of wine. Emission factors for the various operations associated with beer, wine, and whiskey production are shown in Table 6.5-1.

Table 6.5-1. EMISSION FACTORS FOR FERMENTATION PROCESSES
EMISSION FACTOR RATING: E

Type of product	Particulates		Hydrocarbons	
	lb/ton	kg/MT	lb/ton	kg/MT
Beer				
Grain handling[a]	3	1.5	-	-
Drying spent grains, etc.[a]	5	2.5	NA[b]	NA
Whiskey				
Grain handling[a]	3	1.5	-	-
Drying spent grains, etc.[a]	5	2.5	NA	NA
Aging	-	-	10[c]	0.024[d]
Wine	Neg[e]	Neg	Neg[e]	Neg

[a] Based on section on grain processing.
[b] No emission factor available, but emissions do occur.
[c] Pounds per year per barrel of whiskey stored.[2]
[d] Kilograms per year per liter of whiskey stored.
[e] No significant emissions.

References for Section 6.5

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 591-608.

6.6 FISH PROCESSING

6.6.1 Process Description[1]

The canning, dehydration, and smoking of fish, and the manufacture of fish meal and fish oil are the important segments of fish processing. There are two types of fish-canning operations: the "wet-fish" method, in which the trimmed fish are cooked directly in the can, and the "pre-cooked" process, in which the whole fish is cooked and then hand sorted before canning.

A large fraction of the fish received in a cannery is processed into by-products, the most important of which is fish meal. In the manufacture of fish meal, fish scrap from the canning lines is charged to continuous live-steam cookers. After the material leaves the cooker, it is pressed to remove oil and water. The pressed cake is then broken up, usually in a hammer mill, and dried in a direct-fired rotary drier or in a steam-tube rotary drier.

6.6.2 Emissions and Controls[1]

The biggest problem from fish processing is odorous emissions. The principal odorous gases generated during the cooking portion of fish-meal manufacturing are hydrogen sulfide and trimethylamine. Some of the methods used to control odors include adsorption by activated carbon, scrubbing with oxidizing solution, and incineration. The only significant sources of dust emissions in fish processing are the driers and grinders used to handle dried fish meal. Emission factors for fish meal manufacturing are shown in Table 6.6-1.

Table 6.6-1. EMISSION FACTORS FOR FISH MEAL PROCESSING
EMISSION FACTOR RATING: C

Emission source	Particulates		Trimethylamine $(CH_3)_3N$		Hydrogen sulfide (H_2S)	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Cookers, lb/ton (kg/MT) of fish meal produced[a]						
Fresh fish	–	–	0.3	0.15	0.01	0.005
Stale fish	–	–	3.5	1.75	0.2	0.10
Driers, lb/ton (kg/MT) of fish scrap[b]	0.1	0.05	–	–	–	–

[a] Reference 2.
[b] Reference 1.

References for Section 6.6

1. Walsh, R.T., K.D. Luedtke, and L.K. Smith. Fish Canneries and Fish Reduction Plants. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS. National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 760-770.

2. Summer, W. Methods of Air Deodorization. New York. Elsevier Publishing Company. p. 284-286.

6.7 MEAT SMOKEHOUSES

6.7.1 Process Description[1]

Smoking is a diffusion process in which food products are exposed to an atmosphere of hardwood smoke, causing various organic compounds to be absorbed by the food. Smoke is produced commercially in the United States by three major methods: (1) by burning dampened sawdust (20 to 40 percent moisture), (2) by burning dry sawdust (5 to 9 percent moisture) continuously, and (3) by friction. Burning dampened sawdust and kiln-dried sawdust are the most widely used methods. Most large, modern, production meat smokehouses are the recirculating type, in which smoke is circulated at reasonably high temperatures throughout the smokehouse.

6.7.2 Emissions and Controls[1]

Emissions from smokehouses are generated from the burning hardwood rather than from the cooked product itself. Based on approximately 110 pounds of meat smoked per pound of wood burned (110 kilograms of meat per kilogram of wood burned), emission factors have been derived for meat smoking and are presented in Table 6.7-1.

Emissions from meat smoking are dependent on several factors, including the type of wood, the type of smoke generator, the moisture content of the wood, the air supply, and the amount of smoke recirculated. Both low-voltage electrostatic precipitators and direct-fired afterburners may be used to reduce particulate and organic emissions. These controlled emission factors have also been shown in Table 6.7-1.

Table 6.7-1. EMISSION FACTORS FOR MEAT SMOKING[a,b]
EMISSION FACTOR RATING: D

Pollutant	Uncontrolled		Controlled[c]	
	lb/ton of meat	kg/MT of meat	lb/ton of meat	kg/MT of meat
Particulates	0.3	0.15	0.1	0.05
Carbon monoxide	0.6	0.3	Neg[d]	Neg
Hydrocarbons (CH_4)	0.07	0.035	Neg	Neg
Aldehydes (HCHO)	0.08	0.04	0.05	0.025
Organic acids (acetic)	0.2	0.10	0.1	0.05

[a] Based on 110 pounds of meat smoked per pound of wood burned (110 kg meat/kg wood burned).

[b] References 2, 3, and section on charcoal production.

[c] Controls consist of either a wet collector and low-voltage precipitator in series or a direct-fired afterburner.

[d] With afterburner.

References for Section 6.7

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Carter, E. Private communication between Maryland State Department of Health and Resources Research, Incorporated. November 21, 1969.

3. Polglase, W.L., H.F. Dey, and R.T. Walsh. Smokehouses. In: Air Pollution Engineering Manual. Danielson, J. A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 750-755.

6.8 NITRATE FERTILIZERS

6.8.1 General[1,2]

For this report, nitrate fertilizers are defined as the product resulting from the reaction of nitric acid and ammonia to form ammonium nitrate solutions or granules. Essentially three steps are involved in producing ammonium nitrate: neutralization; evaporation of the neutralized solution, and control of the particle size and characteristics of the dry product.

Anhydrous ammonia and nitric acid (57 to 65 percent HNO_3)[3,4] are brought together in the neutralizer to produce ammonium nitrate. An evaporator or concentrator is then used to increase the ammonium nitrate concentration. The resulting solutions may be formed into granules by the use of prilling towers or by ordinary granulators. Limestone may be added in either process in order to produce calcium ammonium nitrate.[5,6]

6.8.2 Emissions and Controls

The main emissions from the manufacture of nitrate fertilizers occur in the neutralization and drying operations. By keeping the neutralization process on the acidic side, losses of ammonia and nitric oxides are kept at a minimum. Nitrate dust or particulate matter is produced in the granulation or prilling operation. Particulate matter is also produced in the drying, cooling, coating, and material handling operations. Additional dust may escape from the bagging and shipping facilities.

Typical operations do not use collection devices on the prilling tower. Wet or dry cyclones, however, are used for various granulating, drying, or cooling operations in order to recover valuable products. Table 6.8-1 presents emission factors for the manufacture of nitrate fertilizers.

Table 6.8-1. EMISSION FACTORS FOR NITRATE FERTILIZER MANUFACTURING WITHOUT CONTROLS
EMISSION FACTOR RATING: B

Type of process[a]	Particulates		Nitrogen oxides (NO_x)		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
With prilling tower[b]						
Neutralizer[c,d]	–	–	–	–	2	1
Prilling tower	0.9	0.45	–	–	–	–
Dryers and coolers[e]	12	6	–	–	–	–
With granulator[b]						
Neutralizer[c,d]	–	–	–	–	2	1
Granulator[e]	0.4	0.2	0.9	0.45	0.5	0.25
Dryers and coolers[e,f]	7	3.5	3	1.5	1.3	0.65

[a] Plants will use either a prilling tower or a granulator but not both.

[b] Reference 7.

[c] Reference 8.

[d] Controlled factor based on 95 percent recovery in recycle scrubber.

[e] Use of wet cyclones can reduce emissions by 70 percent.

[f] Use of wet screen scrubber following cyclone can reduce emissions by 95 to 97 percent.

References for Section 6.8

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Stern, A. (ed.). Sources of Air Pollution and Their Control. In: Air Pollution Vol. III, 2nd Ed. New York, Academic Press. 1968. p. 231-234.

3. Sauchelli, V. Chemistry and Technology of Fertilizers. New York, Reinhold Publishing Company. 1960.

4. Falck-Muus, R. New Process Solves Nitrate Corrosion. Chem. Eng. 74(14):108, July 3, 1967.

5. Ellwood, P. Nitrogen Fertilizer Plant Integrates Dutch and American Know-How. Chem. Eng. p. 136-138, May 11, 1964.

6. Chemico, Ammonium Nitrate Process Information Sheets.

7. Unpublished source sampling data. Resources Research, Incorporated. Reston, Virginia.

8. Private communication with personnel from Gulf Design Corporation. Lakeland, Florida.

6.9 ORCHARD HEATERS

by Dennis H. Ackerson

6.9.1 General[1-6]

Orchard heaters are commonly used in various areas of the United States to prevent frost damage to fruit and fruit trees. The five common types of orchard heaters—pipeline, lazy flame, return stack, cone, and solid fuel—are shown in Figure 6.9-1. The pipeline heater system is operated from a central control and fuel is distributed by a piping system from a centrally located tank. Lazy flame, return stack, and cone heaters contain integral fuel reservoirs, but can be converted to a pipeline system. Solid fuel heaters usually consist only of solid briquettes, which are placed on the ground and ignited.

The ambient temperature at which orchard heaters are required is determined primarily by the type of fruit and stage of maturity, by the daytime temperatures, and by the moisture content of the soil and air.

During a heavy thermal inversion, both convective and radiant heating methods are useful in preventing frost damage; there is little difference in the effectiveness of the various heaters. The temperature response for a given fuel rate is about the same for each type of heater as long as the heater is clean and does not leak. When there is little or no thermal inversion, radiant heat provided by pipeline, return stack, or cone heaters is the most effective method for preventing damage.

Proper location of the heaters is essential to the uniformity of the radiant heat distributed among the trees. Heaters are usually located in the center space between four trees and are staggered from one row to the next. Extra heaters are used on the borders of the orchard.

6.9.2 Emissions[1-6]

Emissions from orchard heaters are dependent on the fuel usage rate and the type of heater. Pipeline heaters have the lowest particulate emission rates of all orchard heaters. Hydrocarbon emissions are negligible in the pipeline heaters and in lazy flame, return stack, and cone heaters that have been converted to a pipeline system. Nearly all of the hydrocarbon losses are evaporative losses from fuel contained in the heater reservoir. Because of the low burning temperatures used, nitrogen oxide emissions are negligible.

Emission factors for the different types of orchard heaters are presented in Table 6.9-1 and Figure 6.9-2.

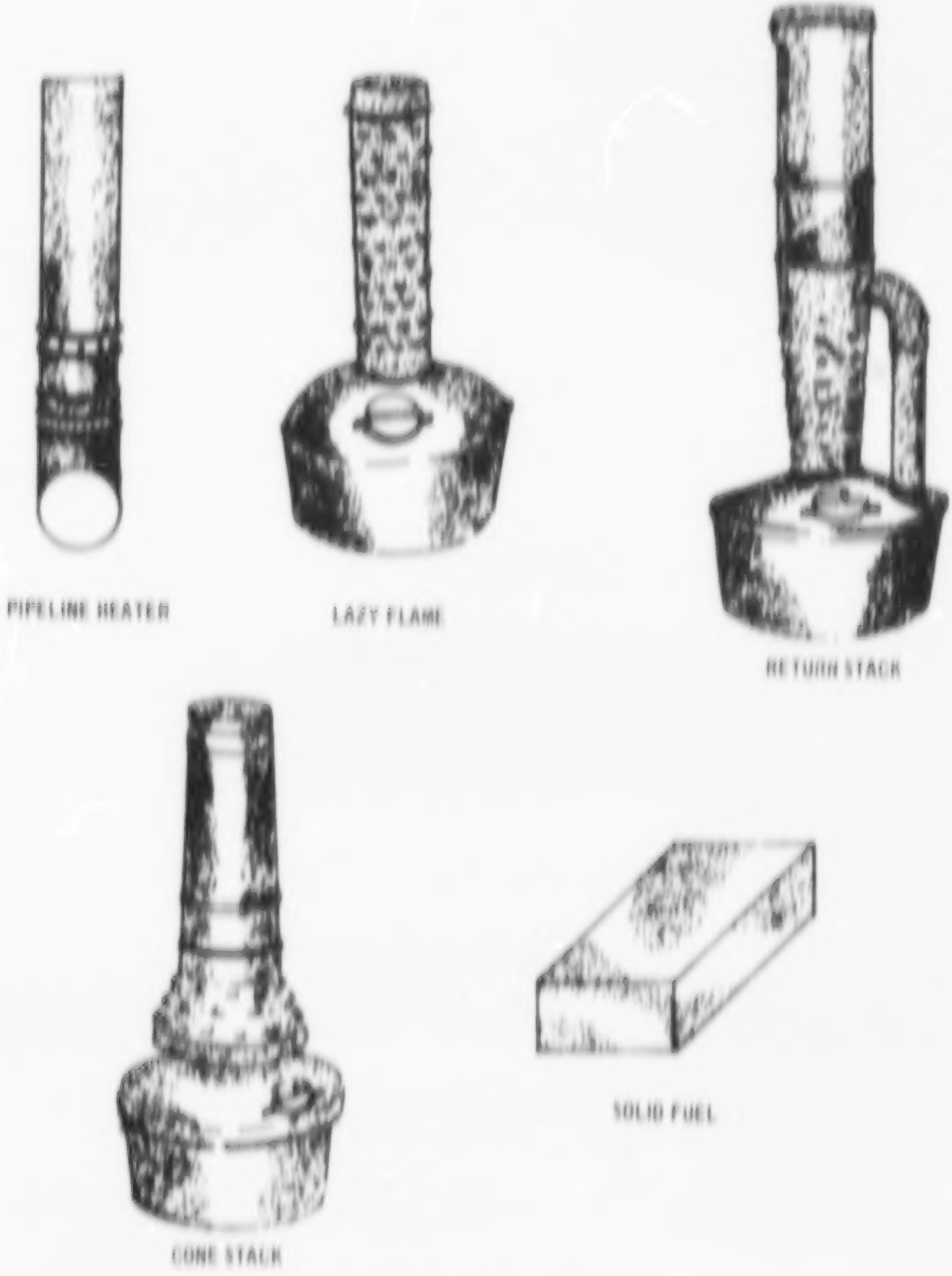
PIPELINE HEATER
LAZY FLAME
RETURN STACK
CONE STACK
SOLID FUEL

Figure 6.9-1. Types of orchard heaters.6

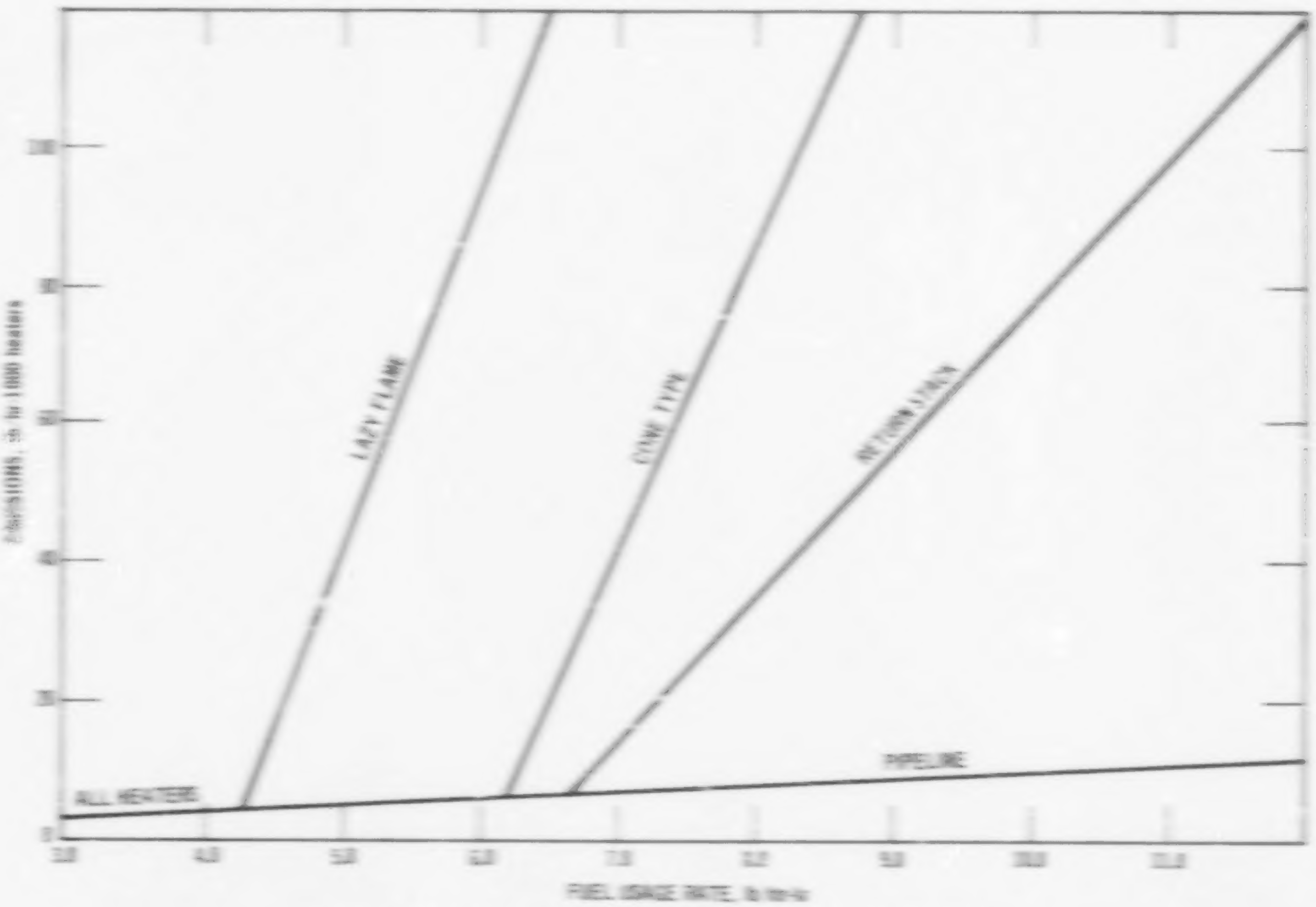

Figure 6.9-2. Particulate emissions from orchard heaters.[3,6]

Table 6.9-1. EMISSION FACTORS FOR ORCHARD HEATERS[a]
EMISSION FACTOR RATING: C

Pollutant	Type of heater				
	Pipeline	Lazy flame	Return stack	Cone	Solid fuel
Particulate					
lb/htr-hr	b	b	b	b	0.05
kg/htr-hr	b	b	b	b	0.023
Sulfur oxides					
lb/htr-hr	0.13S[d]	0.11S	0.14S	0.14S	NA[e]
kg/htr-hr	0.06S	0.05S	0.06S	0.06S	NA
Carbon monoxide					
lb/htr-hr	6.2	NA	NA	NA	NA
kg/htr-hr	2.8	NA	NA	NA	NA
Hydrocarbons[f]					
lb/htr-yr	Neg[g]	16.0	16.0	16.0	Neg
kg/htr-yr	Neg	7.3	7.3	7.3	Neg
Nitrogen oxides[h]					
lb/htr-hr	Neg	Neg	Neg	Neg	Neg
kg/htr-hr	Neg	Neg	Neg	Neg	Neg

[a] References 1, 3, 4 and 6.

[b] Particulate emissions for pipeline, lazy flame, return stack, and cone heaters are shown in Figure 6.9-2.

[c] Based on emission factors for fuel oil combustion in Section 1.3.

[d] S = sulfur content.

[e] Not available.

[f] Based on emission factors for fuel oil combustion in Section 1.3. Evaporative losses only. Hydrocarbon emissions from combustion are considered negligible. Evaporative hydrocarbon losses for units that are part of a pipeline system are negligible.

[g] Negligible.

[h] Little nitrogen oxide is formed because of the relatively low combustion temperatures.

References for Section 6.9

1. Air Pollution in Ventura County. County of Ventura Health Department. Santa Paula, Calif. June 1966.

2. Frost Protection in Citrus. Agricultural Extension Service, University of California. Ventura. November 1967.

3. Personal communication with Mr. Wesley Snowden. Valentine, Fisher, and Tomlinson, Consulting Engineers. Seattle, Washington. May 1971.

4. Communication with the Smith Energy Company. Los Angeles, Calif. January 1968.

5. Communication with Agricultural Extension Service, University of California. Ventura, Calif. October 1969.

6. Personal communication with Mr. Ted Wakai. Air Pollution Control District, County of Ventura. Ojai, Calif. May 1972.

6.10 PHOSPHATE FERTILIZERS

Nearly all phosphatic fertilizers are made from naturally occurring, phosphorus-containing minerals such as phosphate rock. Because the phosphorus content of these minerals is not in a form that is readily available to growing plants, the minerals must be treated to convert the phosphorus to a plant-available form. This conversion can be done either by the process of acidulation or by a thermal process. The intermediate steps of the mining of phosphate rock and the manufacture of phosphoric acid are not included in this section as they are discussed in other sections of this publication; it should be kept in mind, however, that large integrated plants may have all of these operations taking place at one location.

In this section phosphate fertilizers have been divided into three categories: (1) normal superphosphate, (2) triple superphosphate, and (3) ammonium phosphate. Emission factors for the various processes involved are shown in Table 6.10-1.

Table 6.10-1. EMISSION FACTORS FOR THE PRODUCTION OF PHOSPHATE FERTILIZERS
EMISSION FACTOR RATING: C

Type of product	Particulates[a]	
	lb/ton	kg/MT
Normal superphosphate[b]		
Grinding, drying	9	4.5
Main stack	–	–
Triple superphosphate[b]		
Run of pile (ROP)	–	–
Granular	–	–
Diammonium phosphate[c]		
Dryer, cooler	80	40
Ammoniator-granulator	2	1

[a] Control efficiencies of 99 percent can be obtained with fabric filters.
[b] References 1 through 3.
[c] References 1, 4, and 5 through 8.

6.10.1 Normal Superphosphate

6.10.1.1 *General*[4,9] Normal superphosphate (also called single or ordinary superphosphate) is the product resulting from the acidulation of phosphate rock with sulfuric acid. Normal superphosphate contains from 16 to 22 percent phosphoric anhydride (P_2O_5). The physical steps involved in making superphosphate are: (1) mixing rock and acid, (2) allowing the mix to assume a solid form (denning), and (3) storing (curing) the material to allow the acidulation reaction to be completed. After the curing period, the product can be ground and bagged for sale, the cured superphosphate can be sold directly as run-of-pile product, or the material can be granulated for sale as granulated superphosphate.

6.10.1.2 Emissions – The gases released from the acidulation of phosphate rock contain silicon tetrafluoride, carbon dioxide, steam, particulates, and sulfur oxides. The sulfur oxide emissions arise from the reaction of phosphate rock and sulfuric acid.[10]

If a granulated superphosphate is produced, the vent gases from the granulator-ammoniator may contain particulates, ammonia, silicon tetrafluoride, hydrofluoric acid, ammonium chloride, and fertilizer dust. Emissions from the final drying of the granulated product will include gaseous and particulate fluorides, ammonia, and fertilizer dust.

6.10.2 Triple Superphosphate

6.10.2.1 General[4,9] – Triple superphosphate (also called double or concentrated superphosphate) is the product resulting from the reaction between phosphate rock and phosphoric acid. The product generally contains 44 to 52 percent P_2O_5, which is about three times the P_2O_5 usually found in normal superphosphates.

Presently, there are three principal methods of manufacturing triple superphosphate. One of these uses a cone mixer to produce a pulverized product that is particularly suited to the manufacture of ammoniated fertilizers. This product can be sold as run-of-pile (ROP), or it can be granulated. The second method produces in a multi-step process a granulated product that is well suited for direct application as a phosphate fertilizer. The third method combines the features of quick drying and granulation in a single step.

6.10.2.2 Emissions – Most triple superphosphate is the nongranular type. The exit gases from a plant producing the nongranular product will contain considerable quantities of silicon tetrafluoride, some hydrogen fluoride, and a small amount of particulates. Plants of this type also emit fluorides from the curing buildings.

In the cases where ROP triple superphosphate is granulated, one of the greatest problems is the emission of dust and fumes from the dryer and cooler. Emissions from ROP granulation plants include silicon tetrafluoride, hydrogen fluoride, ammonia, particulate matter, and ammonium chloride.

In direct granulation plants, wet scrubbers are usually used to remove the silicon tetrafluoride and hydrogen fluoride generated from the initial contact between the phosphoric acid and the dried rock. Screening stations and bagging stations are a source of fertilizer dust emissions in this type of process.

6.10.3 AMMONIUM PHOSPHATE

6.10.3.1 General – The two general classes of ammonium phosphates are monoammonium phosphate and diammonium phosphate. The production of these types of phosphate fertilizers is starting to displace the production of other phosphate fertilizers because the ammonium phosphates have a higher plant food content and a lower shipping cost per unit weight of P_2O_5.

There are various processes and process variations in use for manufacturing ammonium phosphates. In general, phosphoric acid, sulfuric acid, and anhydrous ammonia are allowed to react to produce the desired grade of ammonium phosphate. Potash salts are added, if desired, and the product is granulated, dried, cooled, screened, and stored.

6.10.3.2 Emissions. The major pollutants from ammonium phosphate production are fluoride, particulates, and ammonia. The largest sources of particulate emissions are the cage mills, where oversized products from the screens are ground before being recycled to the ammoniator. Vent gases from the ammoniator tanks are the major source of ammonia. This gas is usually scrubbed with acid, however, to recover the residual ammonia.

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6.11 STARCH MANUFACTURING

6.11.1 Process Description[1]

The basic raw material in the manufacture of starch is dent corn, which contains starch. The starch in the corn is separated from the other components by "wet milling."

The shelled grain is prepared for milling in cleaners that remove both the light chaff and any heavier foreign material. The cleaned corn is then softened by soaking (steeping) it in warm water acidified with sulfur dioxide. The softened corn goes through attrition mills that tear the kernels apart, freeing the germ and loosening the hull. The remaining mixture of starch, gluten, and hulls is finely ground, and the coarser fiber particles are removed by screening. The mixture of starch and gluten is then separated by centrifuges, after which the starch is filtered and washed. At this point it is dried and packaged for market.

6.11.2 Emissions

The manufacture of starch from corn can result in significant dust emissions. The various cleaning, grinding, and screening operations are the major sources of dust emissions. Table 6.11-1 presents emission factors for starch manufacturing.

Table 6.11-1. EMISSION FACTORS
FOR STARCH MANUFACTURING[a]
EMISSION FACTOR RATING: D

Type of operation	Particulates	
	lb/ton	kg/MT
Uncontrolled	8	4
Controlled[b]	0.02	0.01

[a] Reference 2.

[b] Based on centrifugal gas scrubber.

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6.12 SUGAR CANE PROCESSING

6.12.1 General[1]

The processing of sugar cane starts with the harvesting of the crops, either by hand or by mechanical means. If mechanical harvesting is used, much of the unwanted foliage is left, and it thus is standard practice to burn the cane before mechanical harvesting to remove the greater part of the foliage.

After being harvested, the cane goes through a series of processes to be converted to the final sugar product. It is washed to remove larger amounts of dirt and trash; then crushed and shredded to reduce the size of the stalks. The juice is next extracted by one of two methods, milling or diffusion. In milling the cane is pressed between heavy rollers to press out the juice, and in diffusion the sugar is leached out by water and thin juices. The raw sugar then goes through a series of operations including clarification, evaporation, and crystallization in order to produce the final product.

Most mills operate without supplemental fuel because of the sufficient bagasse (the fibrous residue of the extracted cane) that can be burned as fuel.

6.12.2 Emissions

The largest sources of emissions from sugar cane processing are the openfield burning in the harvesting of the crop and the burning of bagasse as fuel. In the various processes of crushing, evaporation, and crystallization, some particulates are emitted but in relatively small quantities. Emission factors for sugar cane processing are shown in Table 6.12-1.

Table 6.12-1. EMISSION FACTORS FOR SUGAR CANE PROCESSING
EMISSION FACTOR RATING: D

Type of process	Particulate	Carbon monoxide	Hydrocarbons	Nitrogen oxides
Field burning[a,b]				
lb/acre burned	225	1,500	300	30
kg/hectare burned	250	1,680	336	33.6
Bagasse burning[c]				
lb/ton bagasse	22	–	–	–
kg/MT bagasse	11	–	–	–

[a] Based on emission factors for open burning of agricultural waste.

[b] There are approximately 4 tons/acre (9,000 kg/hectare) of unwanted foliage on the cane and 11 tons/acre (25,000 kg/hectare) of grass and weed, all of which are combustible.[3]

[c] Reference 2.

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